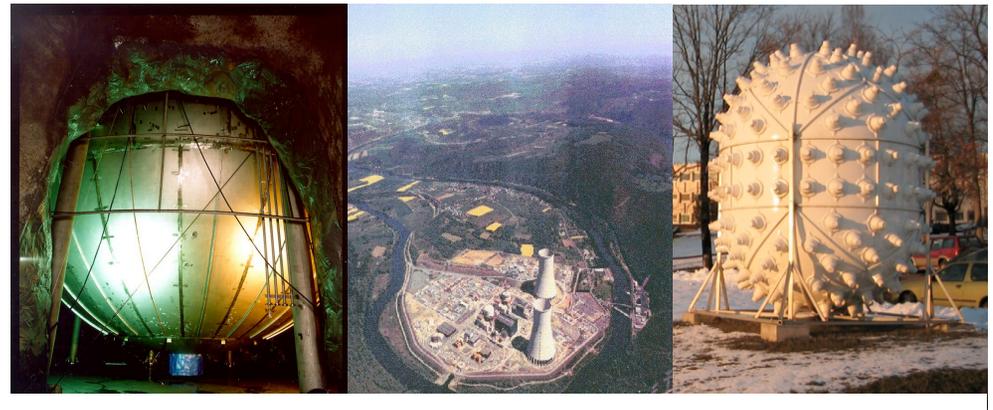
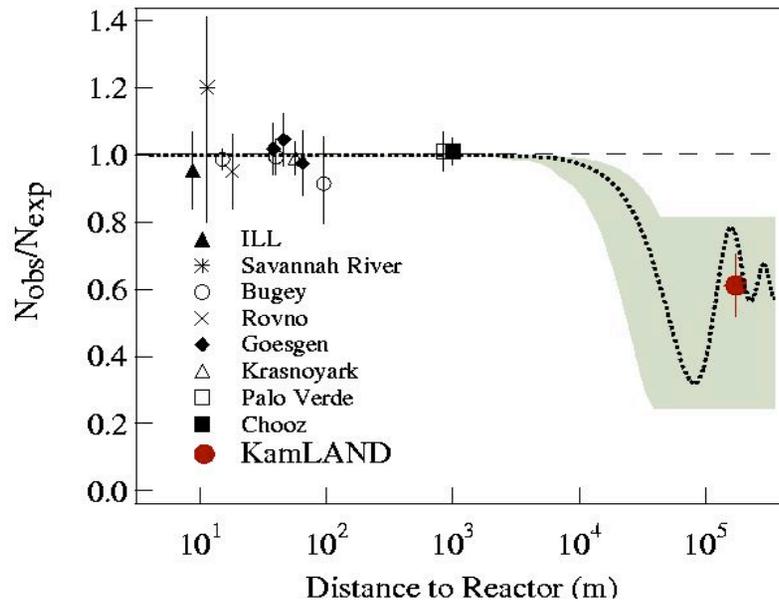
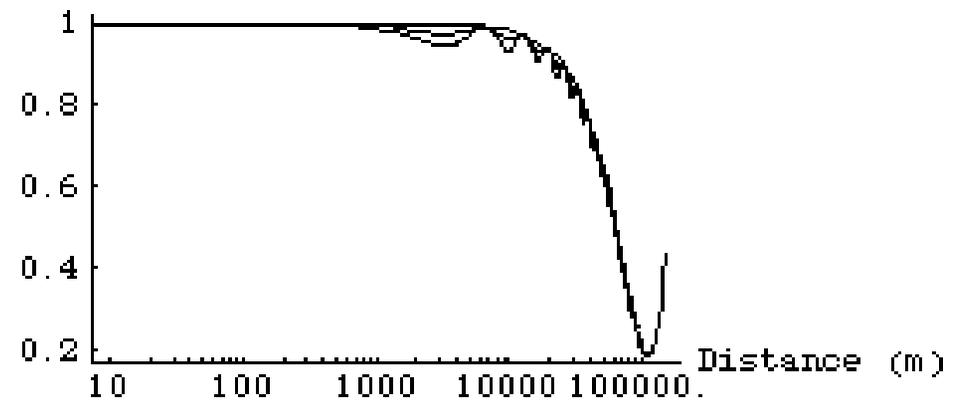


Future Reactor Neutrino Experiments

Novel Neutrino Oscillation Experiments for Measuring the Last Undetermined Neutrino Mixing Angle θ_{13}



Probability

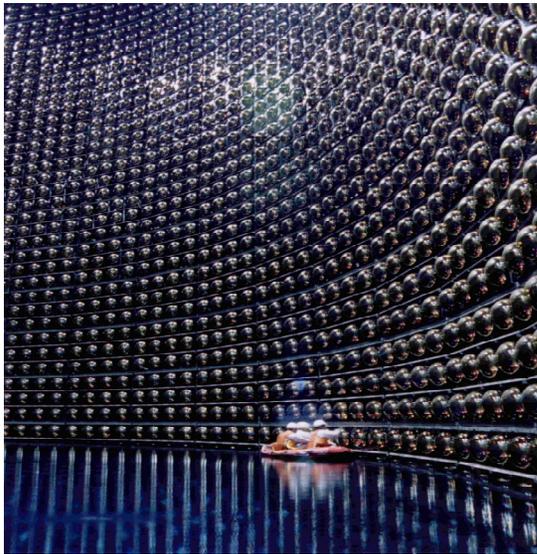


Karsten M. Heeger

Lawrence Berkeley National Laboratory

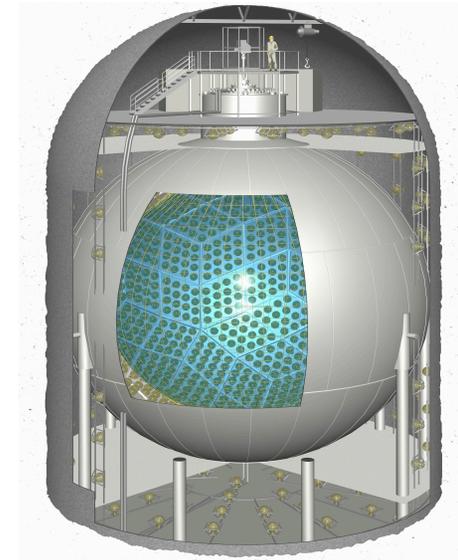
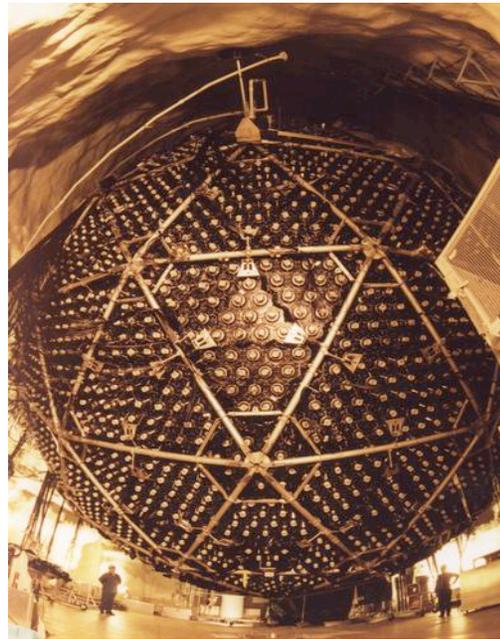
Recent Discoveries in Neutrino Physics

Non-accelerator experiments have changed our understanding of neutrinos



Atmospheric+Solar $\bar{\nu}_e$
(Super-K)

Solar (SNO)



Reactor
(KamLAND)

- Neutrinos are not massless (mass is small: $m_{\nu_e} < 0.0000059 m_e$)
- Evidence for neutrino flavor conversion $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu \leftrightarrow \bar{\nu}_\tau$
- Combination of experimental results show that neutrinos oscillate

U_{MNSP} - Neutrino Mixing Matrix

Present and Future Measurements

Solar	$\theta_{12} = 30.3^\circ$	<i>large</i>
Atmospheric	$\theta_{23} = \sim 45^\circ$	<i>maximal</i>
Chooz + SK	$\tan^2 \theta_{13} < 0.03$ at 90% CL	<i>small ... at best</i>

No good 'ad hoc' model to predict θ_{13} .
 If $\theta_{13} < 10^{-3} \theta_{12}$, perhaps a symmetry?

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \underbrace{\begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ \sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\text{solar } \theta \\ \text{present}}} \underbrace{\begin{pmatrix} \cos \theta_{13} & 0 & e^{i\theta_{CP}} \sin \theta_{13} \\ 0 & 1 & 0 \\ e^{-i\theta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix}}_{\substack{\text{Dirac phase} \\ \text{reactor } \theta_{13} \text{ experiment} \\ \text{reactor and accelerator } \theta \\ \text{future}}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & \sin \theta_{23} & \cos \theta_{23} \end{pmatrix}}_{\substack{\text{atmospheric } \theta \\ \text{present} \\ \text{accelerator } \theta \\ \text{future}}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\theta/2} & 0 \\ 0 & 0 & e^{i\theta/2+i\phi} \end{pmatrix}}_{\substack{\text{Majorana phases} \\ \theta_{CP} \text{ experiments} \\ \text{future}}}$$

Neutrino Oscillation Parameters

Beamstop Neutrinos



$$\bar{\nu}_\mu \bar{\nu}_s \bar{\nu}_e$$

Atmospheric, Reactor, Accelerator Neutrinos



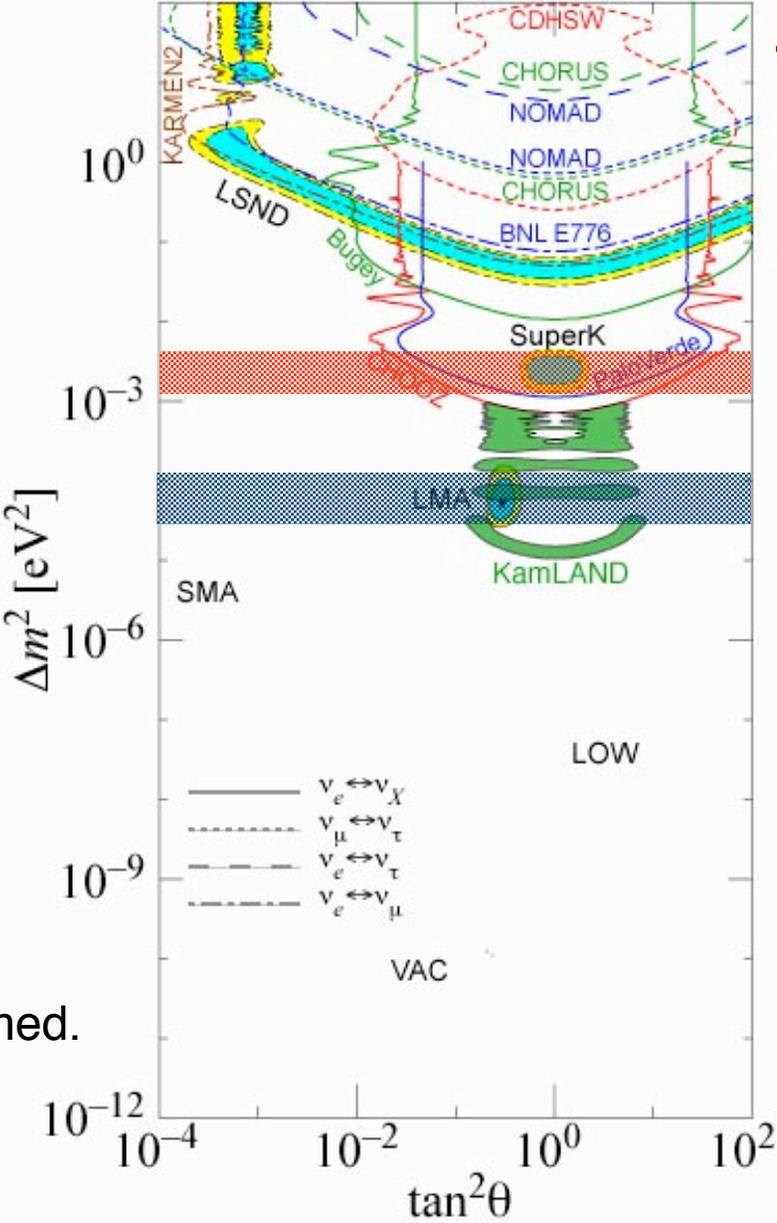
$$\bar{\nu}_\mu \bar{\nu}_\tau$$

Solar and Reactor Neutrinos



$$\bar{\nu}_e \bar{\nu}_{\mu,\tau}$$

Except for LSND, Δm_{ij}^2 measured *and* confirmed.



θ_{13} and \mathcal{CP}

How large is U_{e3} ?

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ \sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\theta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ e^{-i\theta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & \sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\theta/2} & 0 \\ 0 & 0 & e^{i\theta/2+i\phi} \end{pmatrix}$$

solar θ
present

reactor and accelerator θ
future

atmospheric θ
present

0 θ experiments
future

θ_{13} is key parameter for oscillation phenomenology since θ_{12} and θ_{23} are both large

θ_{13} determines whether \mathcal{CP} violation is accessible

\mathcal{CP} proportional to θ_{13}

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\theta_{CP} \sin^2 \frac{m_{12}^2 L}{4E} \sin^2 \frac{m_{13}^2 L}{4E} \sin^2 \frac{m_{23}^2 L}{4E}$$

Why Are Neutrino Oscillation Measurements Important?

Physics at high mass scales, physics of flavor, and unification:

- Why are neutrino masses so small?
- Why are the mixing angles *large, maximal, and small*?
- Is there CP violation, T violation, or CPT violation in the lepton sector?
- Is there a connection between the lepton and the baryon sector?

13

$$U_{MNSP} =$$

$$\begin{bmatrix} \text{big} & \text{big} & \text{small?} \\ \text{big} & \text{big} & \text{big} \\ \text{big} & \text{big} & \text{big} \end{bmatrix}$$



$$V_{CKM} =$$

$$\begin{bmatrix} \text{big} & \text{small} & \text{tiny} \\ \text{small} & \text{big} & \text{tiny} \\ \text{tiny} & \text{tiny} & \text{big} \end{bmatrix}$$

- Understanding the role of neutrinos in the early Universe

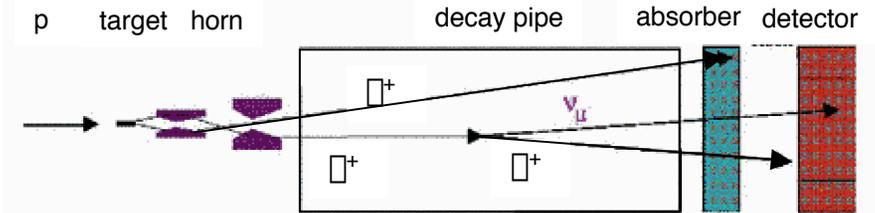


Measuring θ_{13}

Method 1: Accelerator Experiments

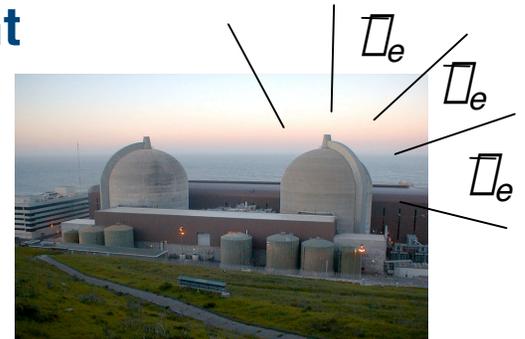
$$P_{\bar{\nu}_e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}^2 L}{4E_{\bar{\nu}_e}} + \dots$$

- appearance experiment $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- measurement of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ yields θ_{13}, θ_{CP}
- baseline $O(100 - 1000 \text{ km})$, matter effects present



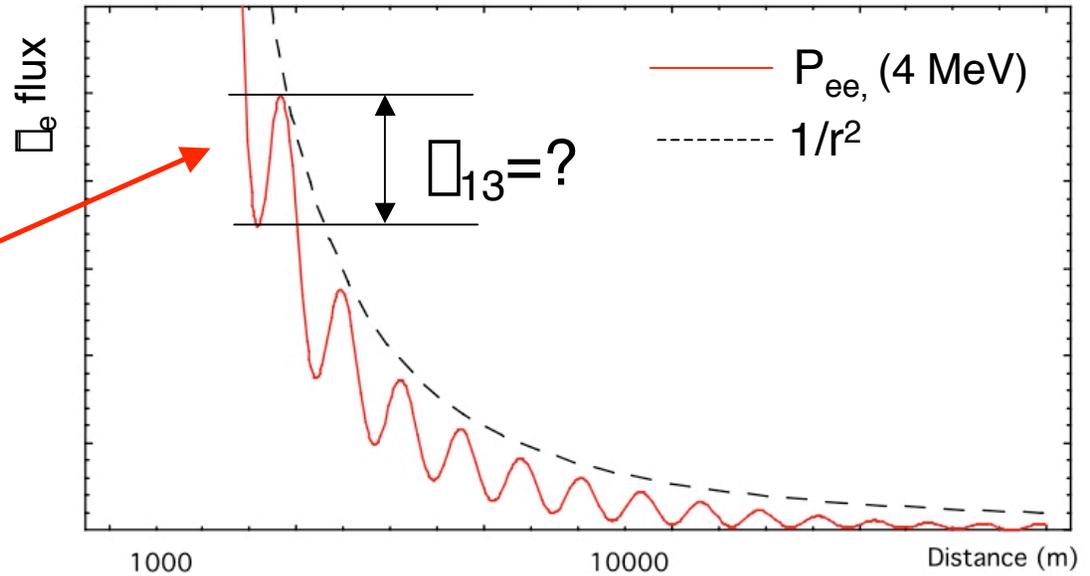
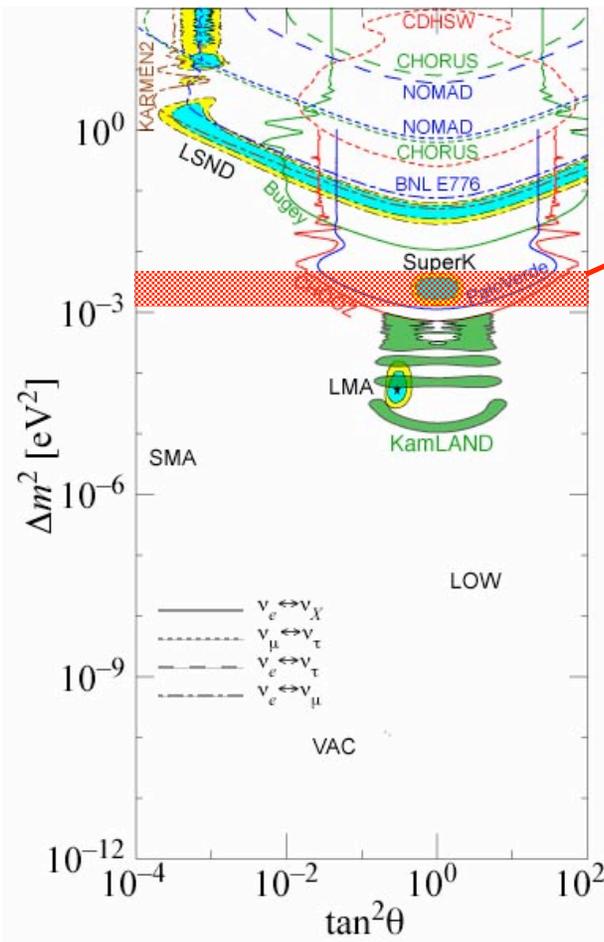
Method 2: Reactor Neutrino Oscillation Experiment

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E_{\bar{\nu}_e}} + \left[\frac{\Delta m_{21}^2 L}{4E_{\bar{\nu}_e}} \right] \cos^4 \theta_{13} \sin^2 2\theta_{13}$$



- disappearance experiment $\bar{\nu}_e \rightarrow \bar{\nu}_x$
- *but*: observation of oscillation signature with 2 or multiple detectors
- look for deviations from $1/r^2$
- baseline $O(1 \text{ km})$, no matter effects

Reactor Neutrino Measurement of θ_{13} - Basic Idea

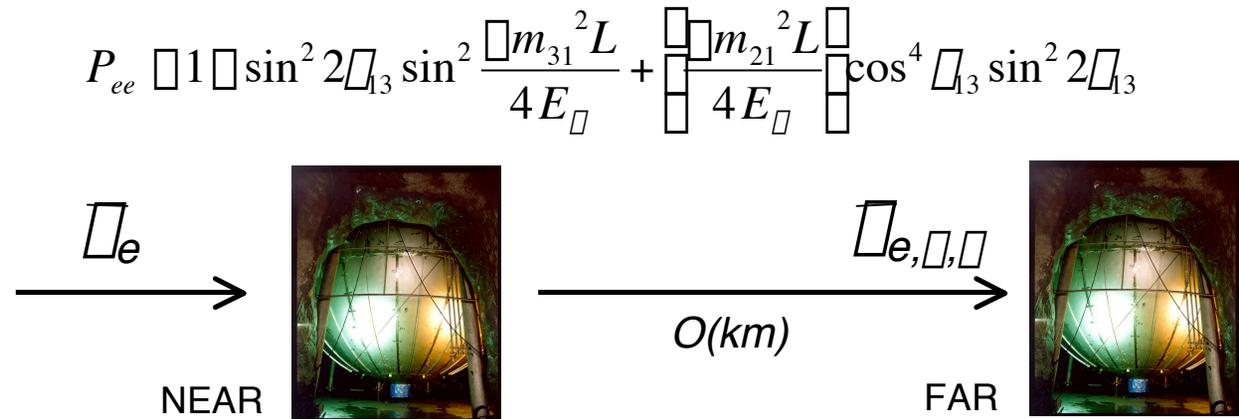
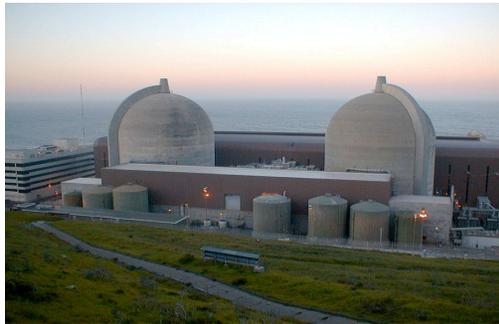


$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{m_{31}^2 L}{4E_\nu} + \frac{\theta_{13} m_{21}^2 L}{4E_\nu} \cos^4 \theta_{13} \sin^2 2\theta_{13}$$

atmospheric frequency dominant

last term negligible for $\frac{\theta_{13} m_{31}^2 L}{4E_\nu} \sim \theta_{13}/2$ and $\sin^2 2\theta_{13} \geq 10^{-3}$

Concept of a Reactor Neutrino Measurement of θ_{13}



2-3 detectors, possibly with variable baseline

- No degeneracies
- No matter effects
- Practically no correlations

Coincidence Signal: $\bar{\nu}_e + p \rightarrow e^+ + n$

Prompt e^+ annihilation
Delayed n capture, ν_s capture time

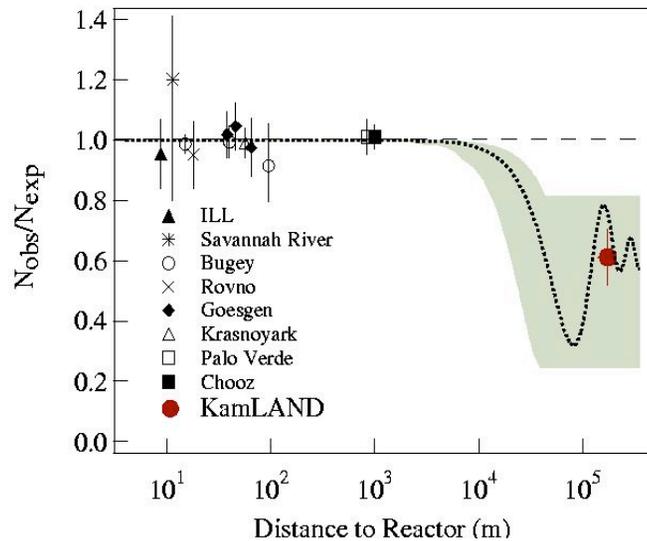
$$E_\nu = E_e + m_n - m_p$$

$$E_{\text{prompt}} = E_{\text{kin}} + 2m_e$$

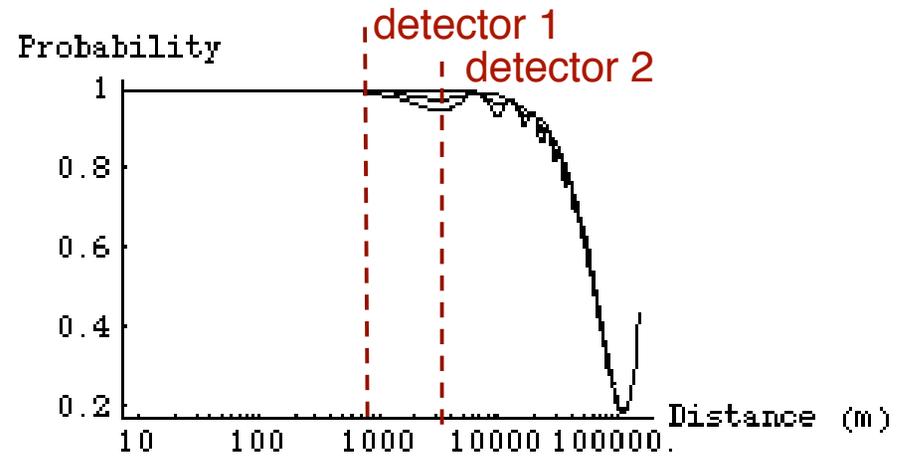
Comparison of near and far detectors $\bar{\nu}_e$ search for spectral distortions

Reactor Neutrino Measurement of θ_{13}

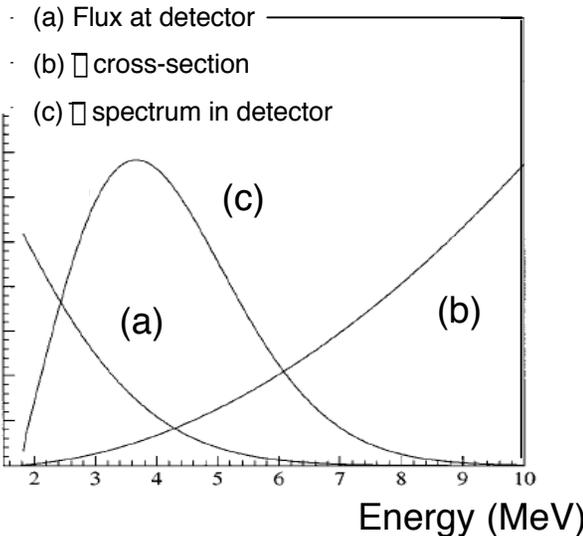
Present Reactor Experiments



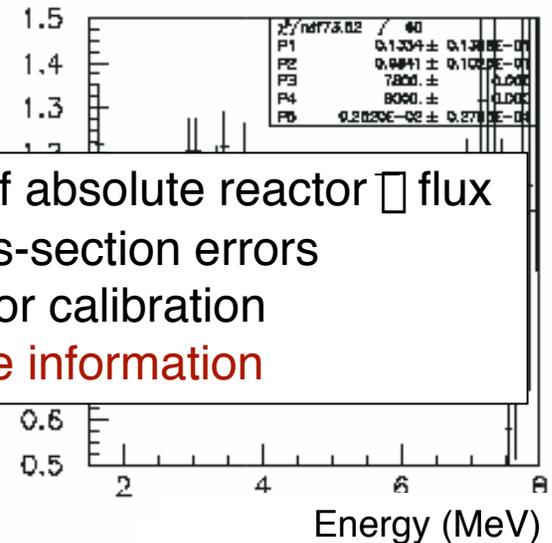
Future θ_{13} Reactor Experiment



Absolute Flux and Spectrum



Ratio of Spectra



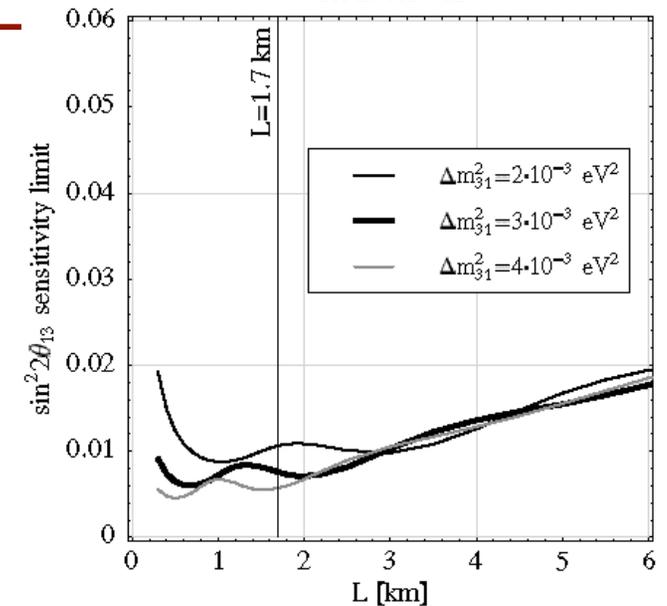
- independent of absolute reactor σ flux
- eliminate cross-section errors
- relative detector calibration
- **rate and shape information**

Baseline Optimization for Detector Placement

I. Undistorted vs Distorted Spectrum

Optimize FAR detector with respect to NEAR

NEAR - FAR 0.1 km (fixed) 1.7 km



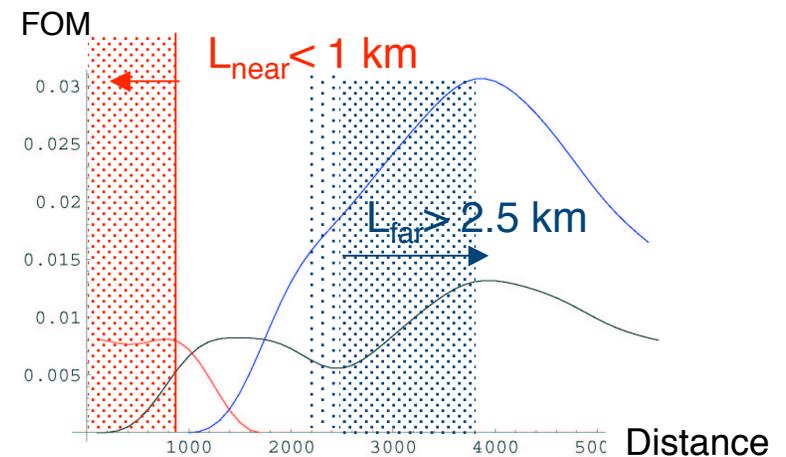
Ref: Huber et al. hep-ph/0303232

II. Maximize Relative Distortions of Spectra

Optimize both detector locations

FAR - FAR 1 km $\sim 2.5\text{-}3 \text{ km}$

Based on shape analysis only



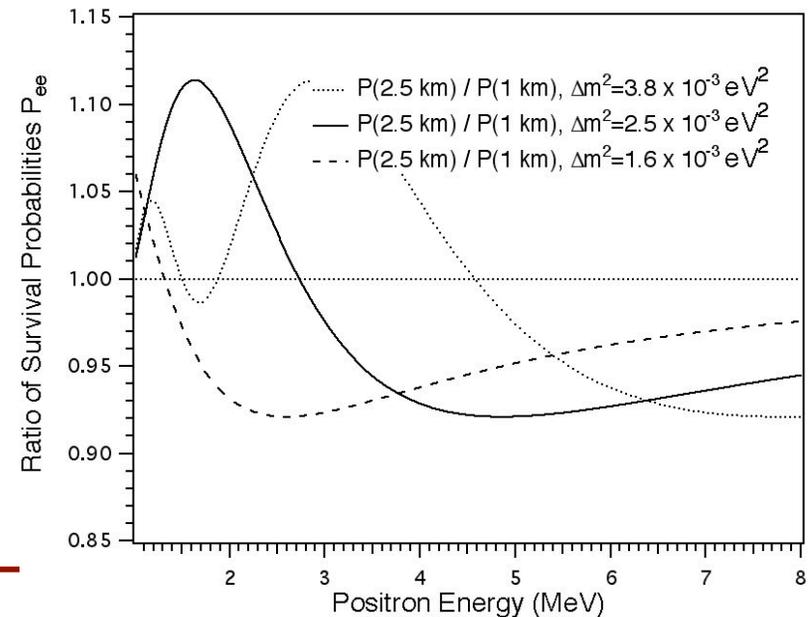
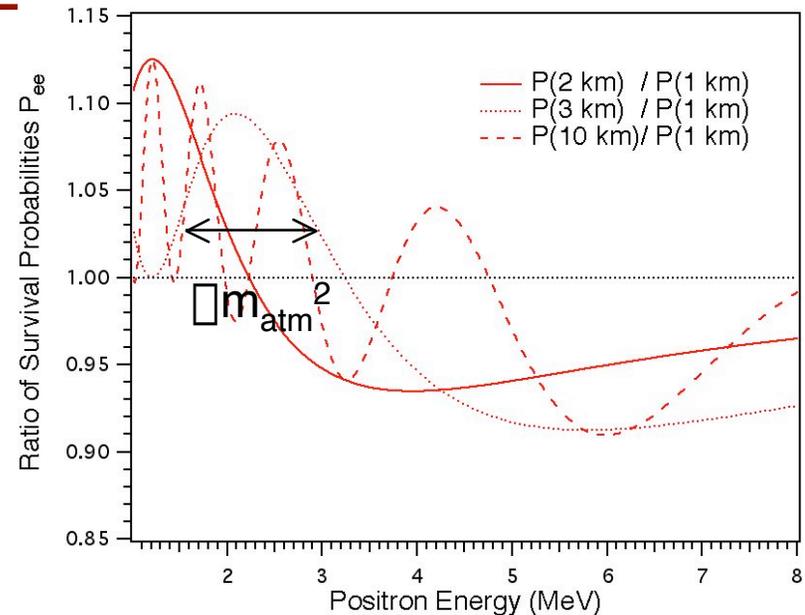
Baseline Optimization for Detector Placement (II)

Advantages of FAR-FAR Configuration

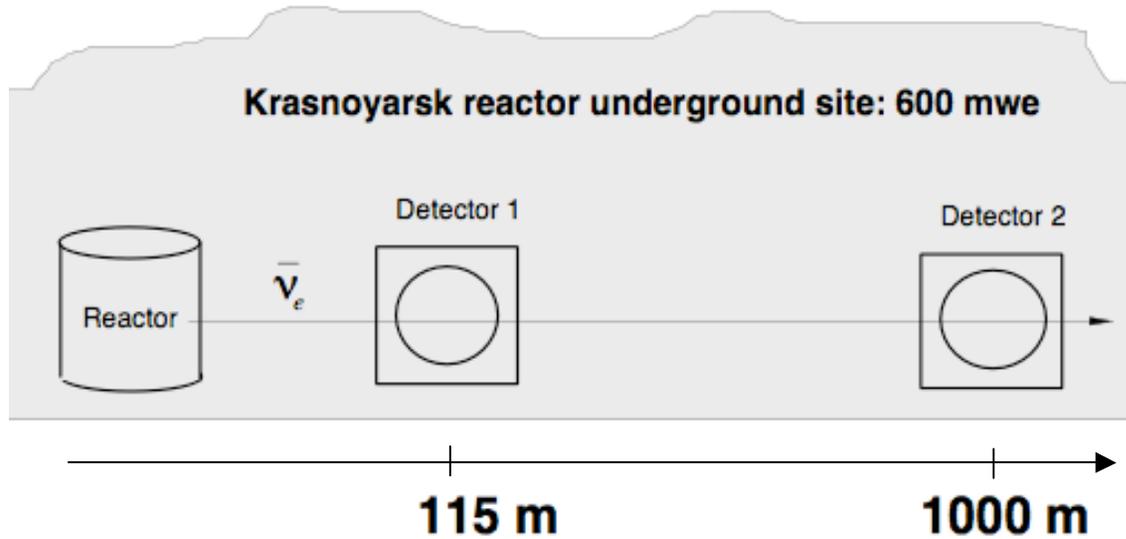
- Oscillation signature in ratio of spectra.
- Avoid power plant boundaries at ~ 1 km.
- Measure Δm_{atm}^2 .

Baseline Sensitivity to Δm_{atm}^2

- Detector baselines sensitive to Δm_{atm}^2 .
- Need option to adjust baseline once we have precision measurement Δm_{atm}^2 .
- Region of interest for current Δm_{atm}^2 region: $L_{\text{far}} \sim 1.5 - 3$ km.



Kr2Det: Reactor $\bar{\nu}_{e13}$ Experiment at Krasnoyarsk

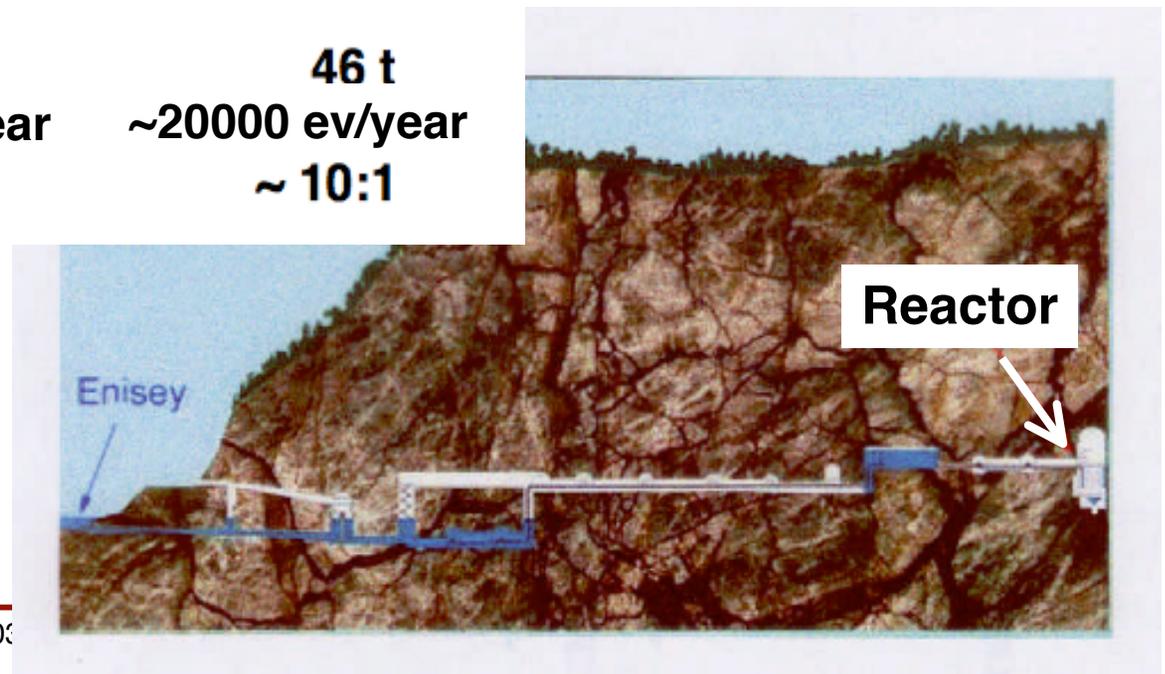


Unique Feature

- underground reactor
- existing infrastructure

Detector locations determined by infrastructure

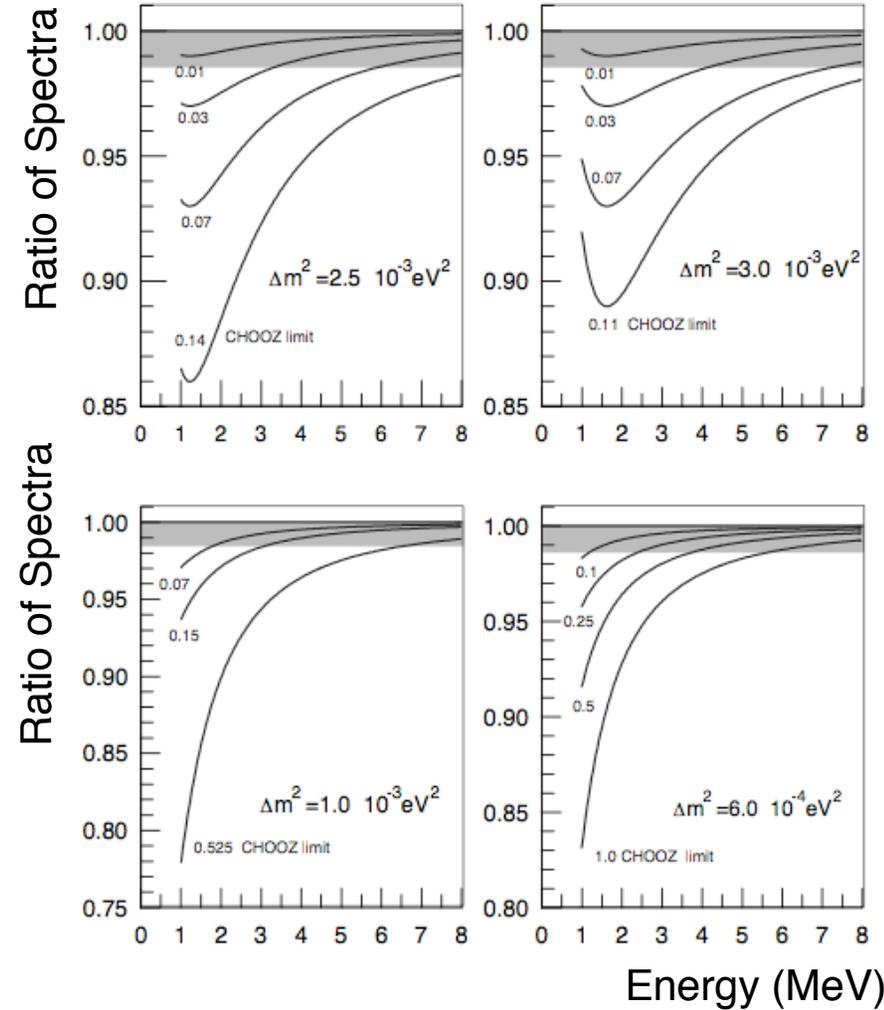
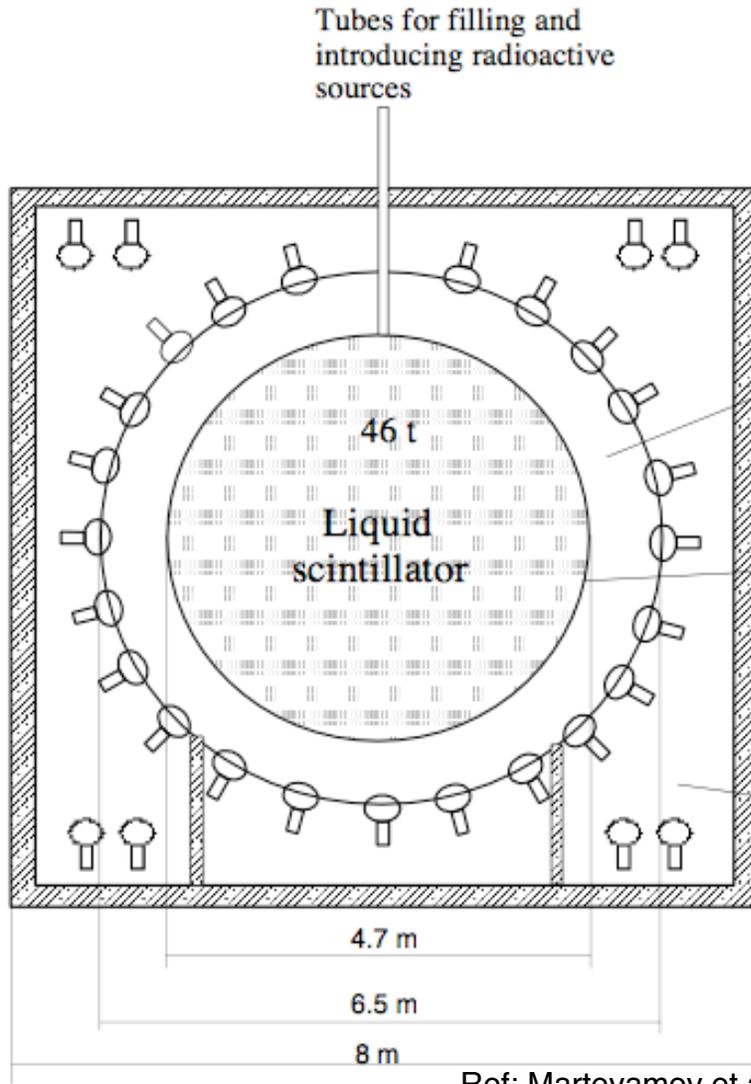
Target:	46 t	46 t
Rate:	$\sim 1.5 \times 10^6$ ev/year	~ 20000 ev/year
S:B	$\gg 1$	$\sim 10:1$



Ref: Marteyamov et al, hep-ex/0211070

Kr2Det: Reactor $\bar{\nu}_{13}$ Experiment at Krasnoyarsk

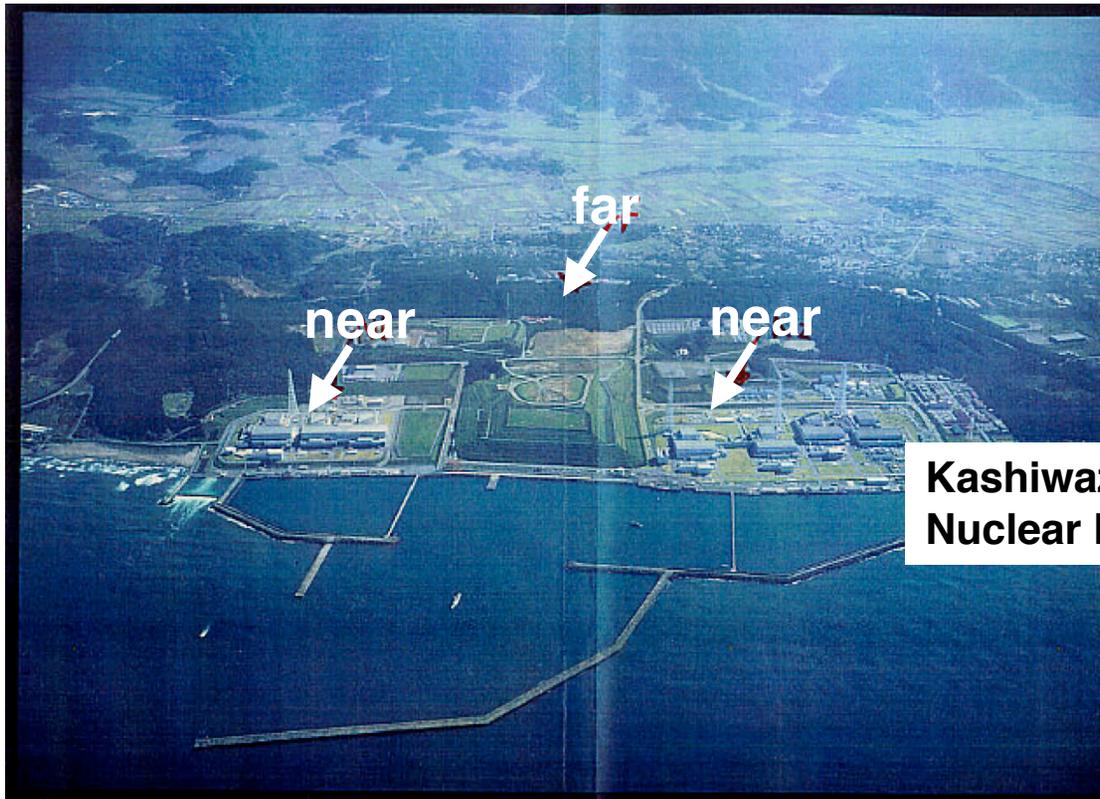
$L_{\text{near}} = 115 \text{ m}$, $L_{\text{far}} = 1000 \text{ m}$, $N_{\text{far}} = 16000/\text{yr}$



Ref: Marteyamov et al., hep-ex/0211070.

Kashiwazaki: Proposal for Reactor \square_{13} Experiment in Japan

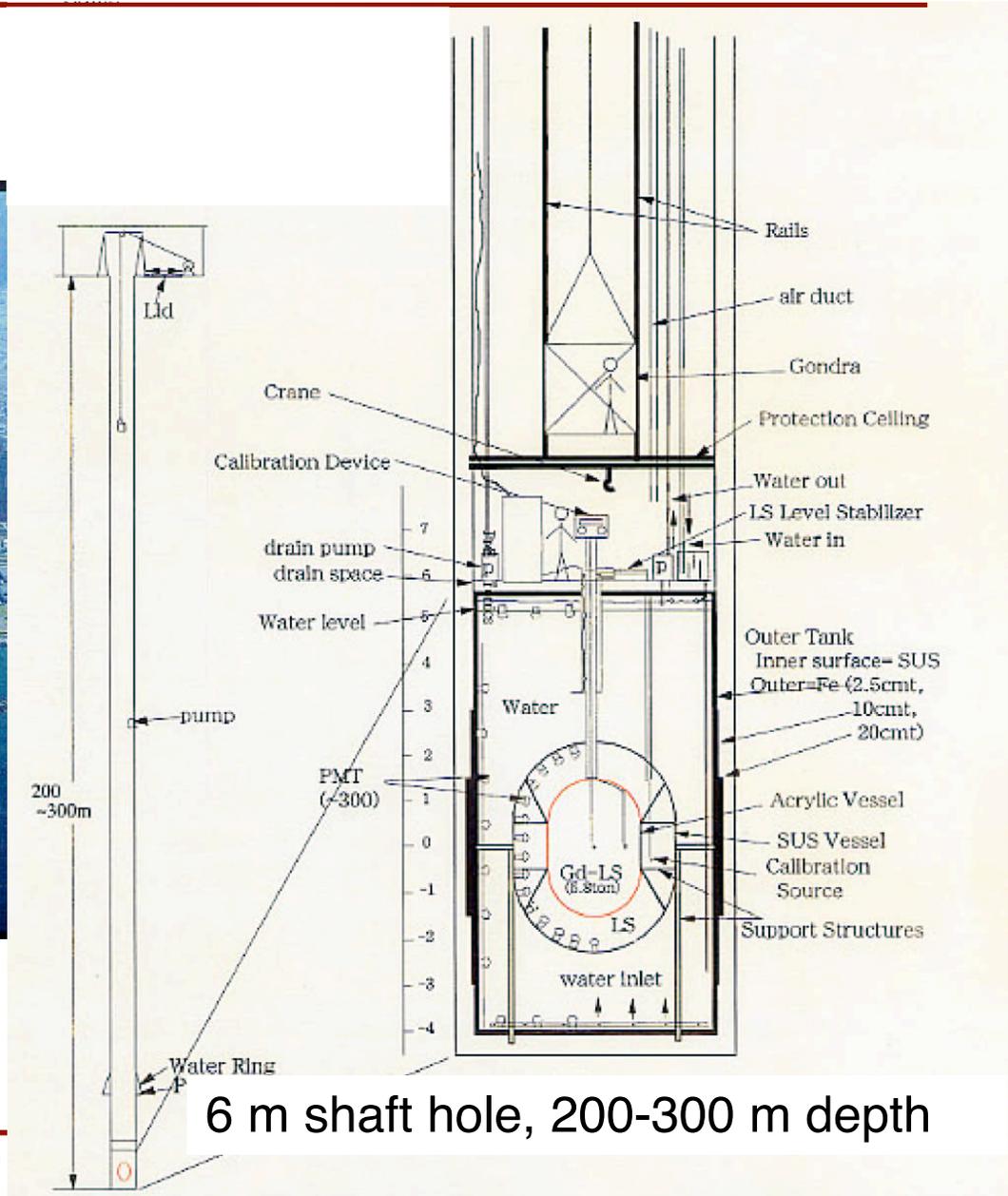
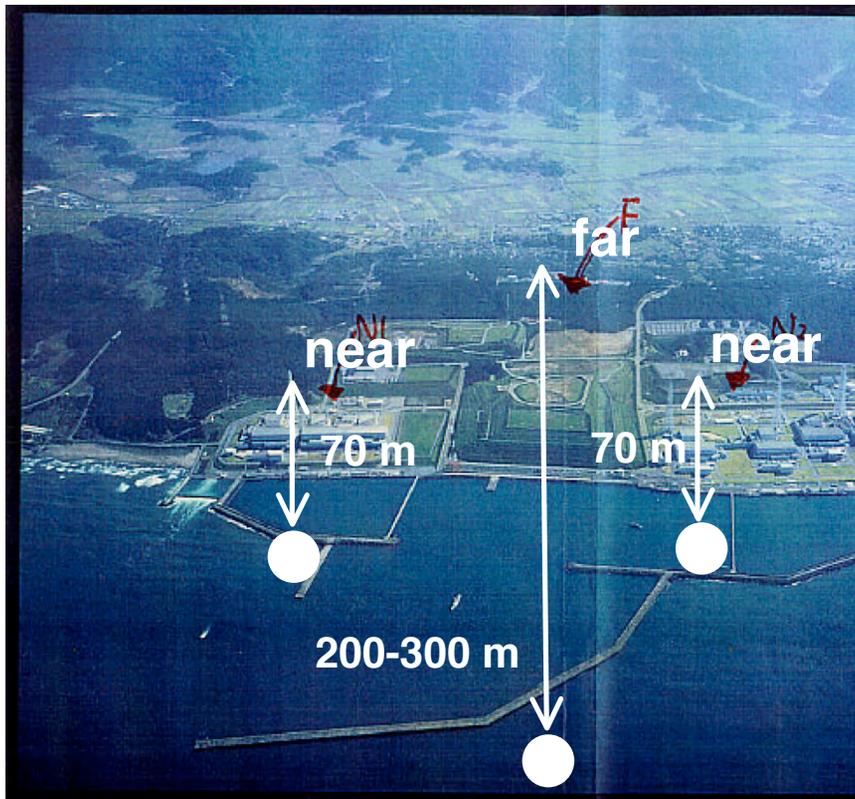
- Kashiwazaki**
- 7 nuclear power stations, World's most powerful reactors
 - requires construction of underground shaft for detectors



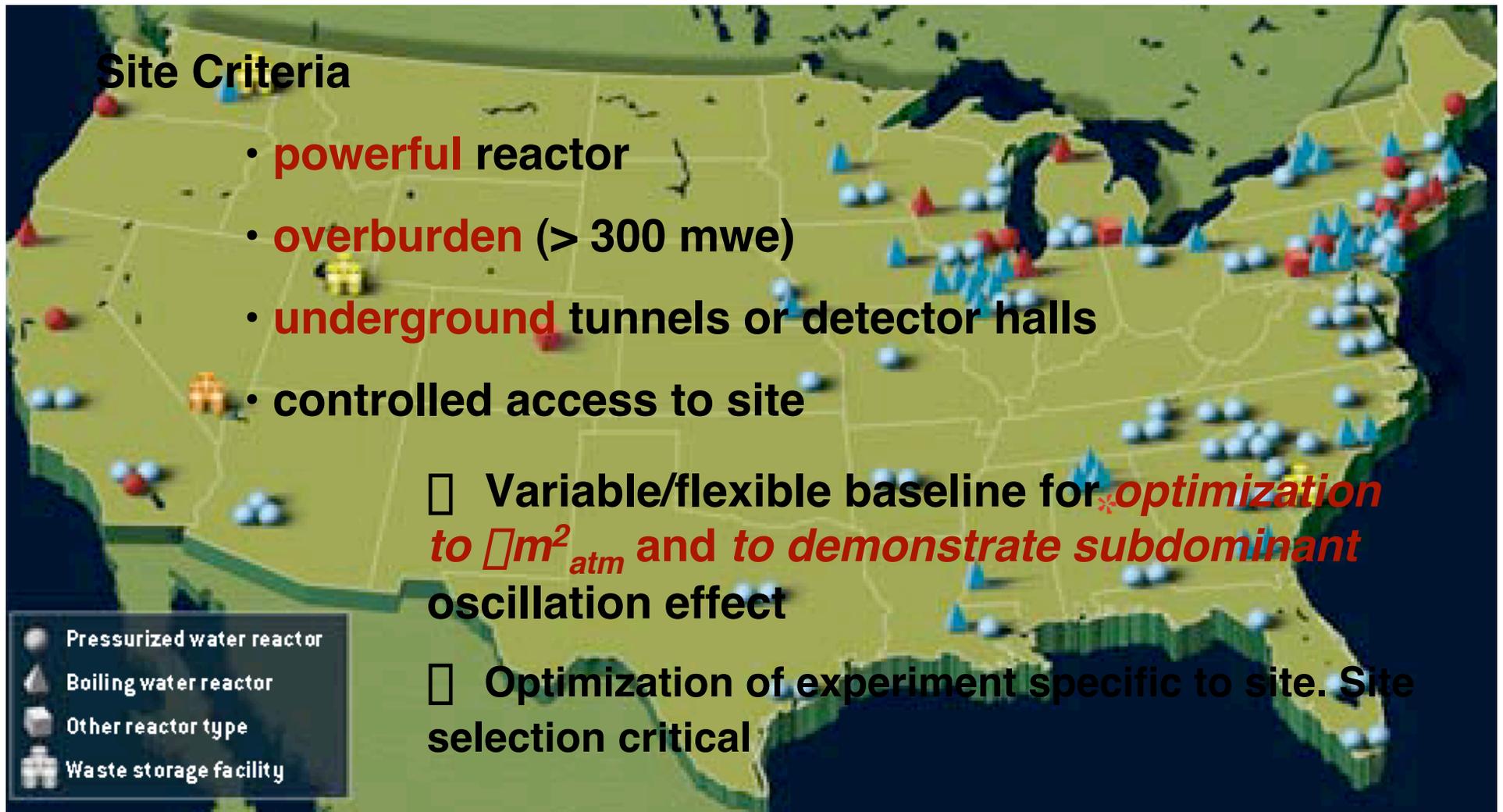
**Kashiwazaki-Kariwa
Nuclear Power Station**



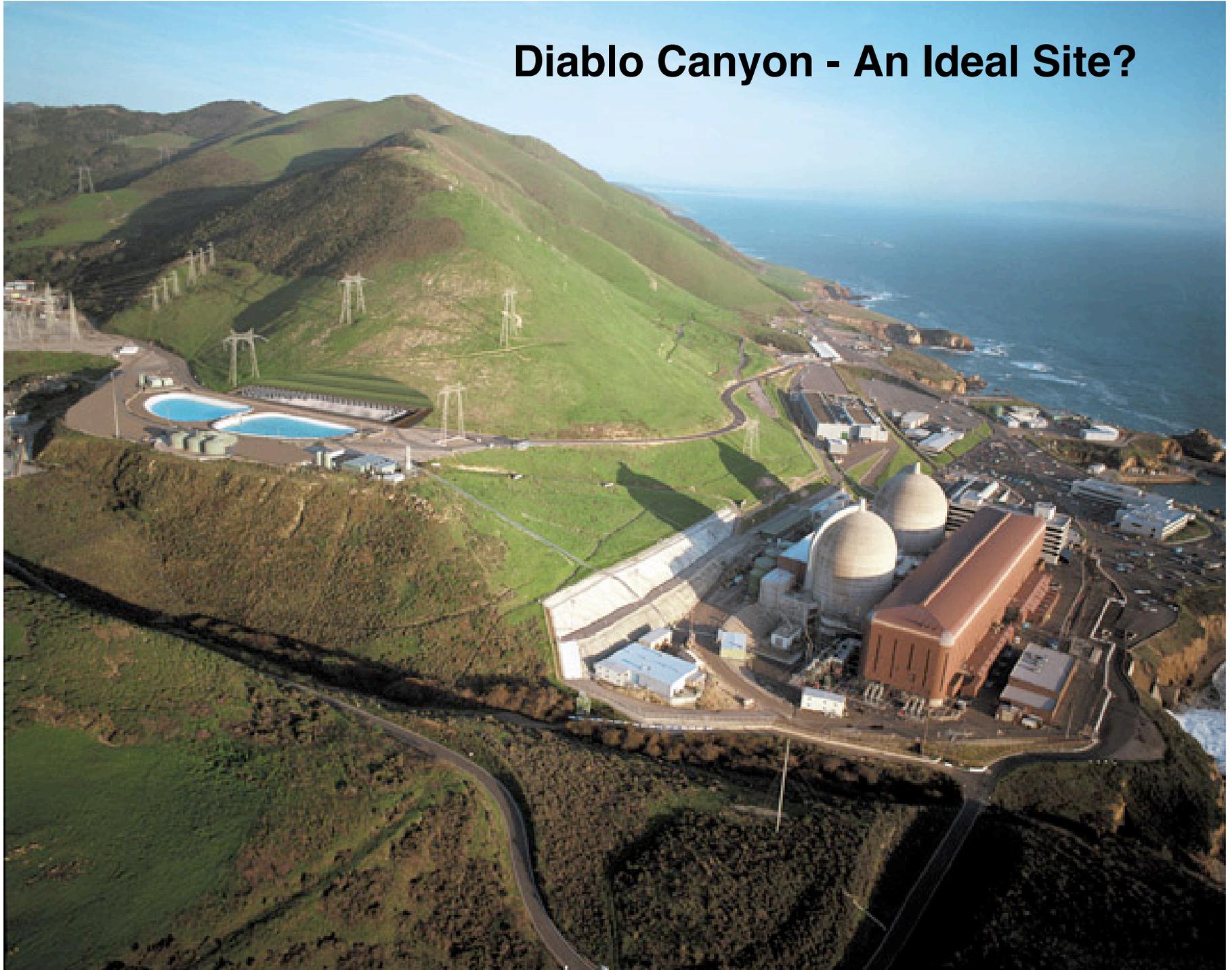
Kashiwazaki: Proposal for Reactor \square_{13} Experiment in Japan



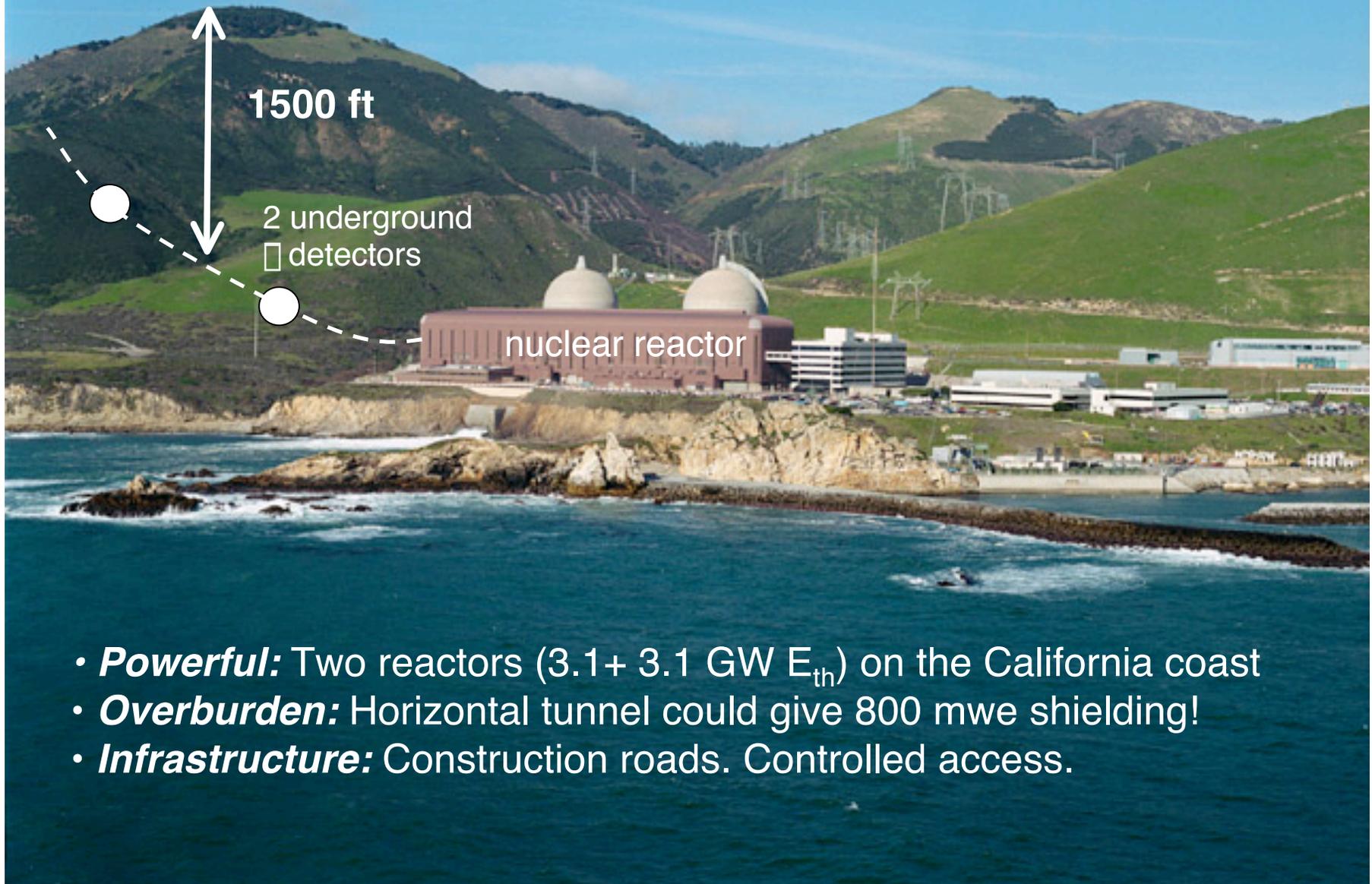
A ν_{13} Reactor Experiment in the US ?

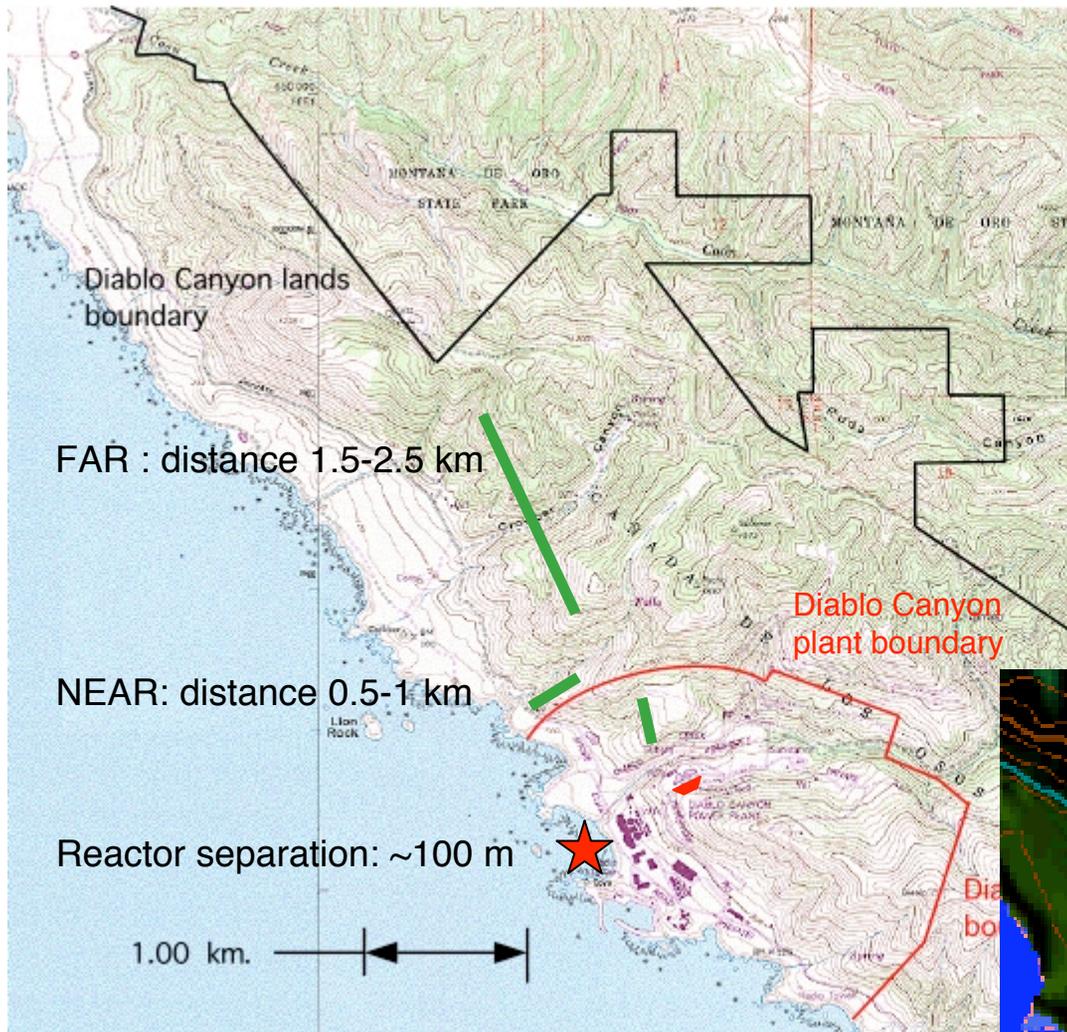


Diablo Canyon - An Ideal Site?



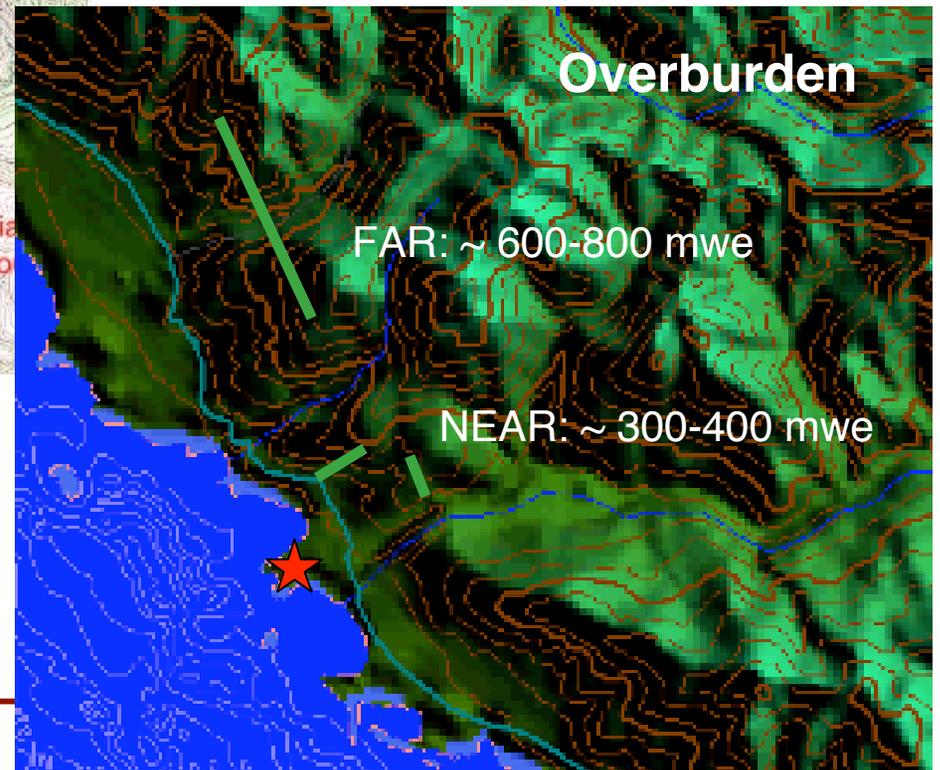
Diablo Canyon - An Ideal Site



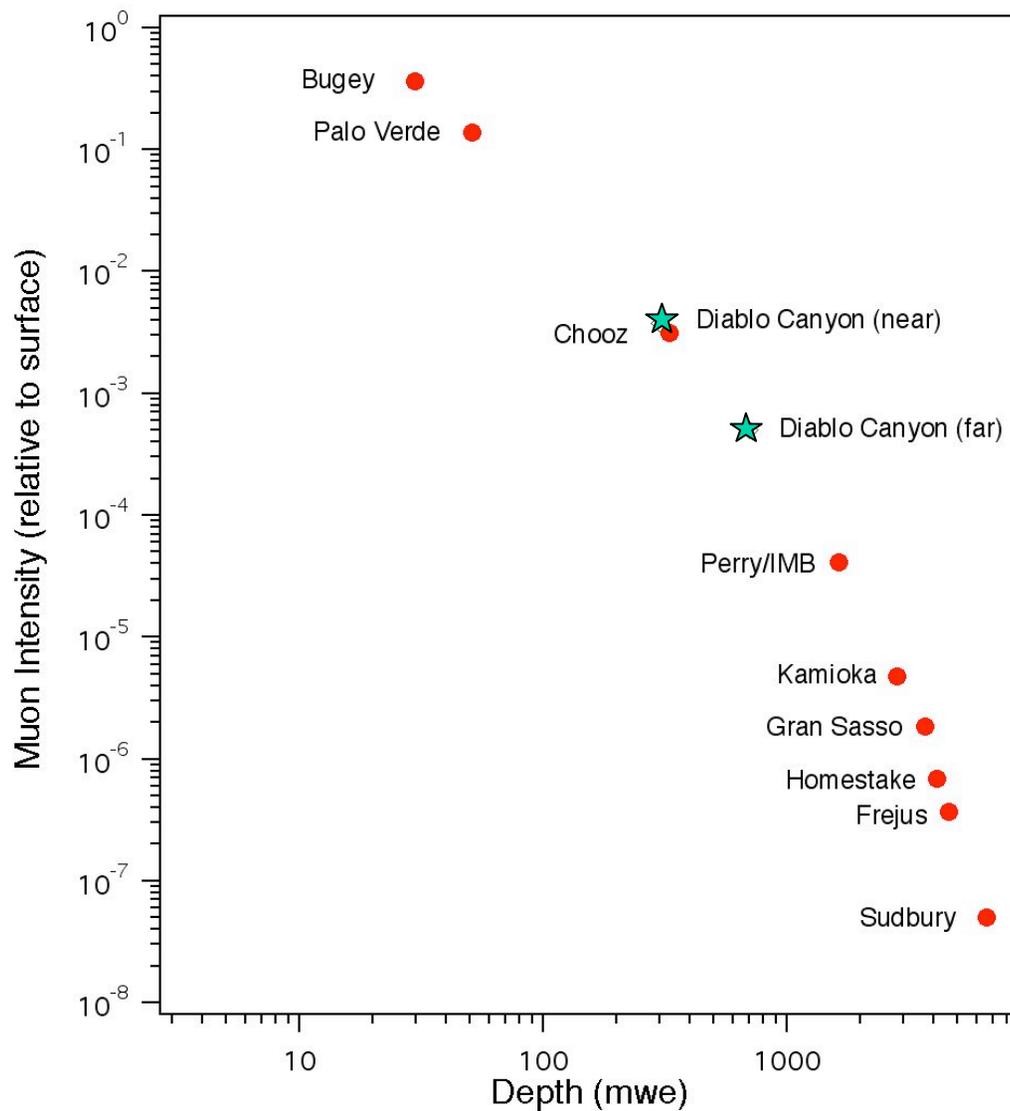


An Ideal Oscillation Experiment with Variable Baseline?

Possible layout of 2 or 3 detectors at Diablo Canyon

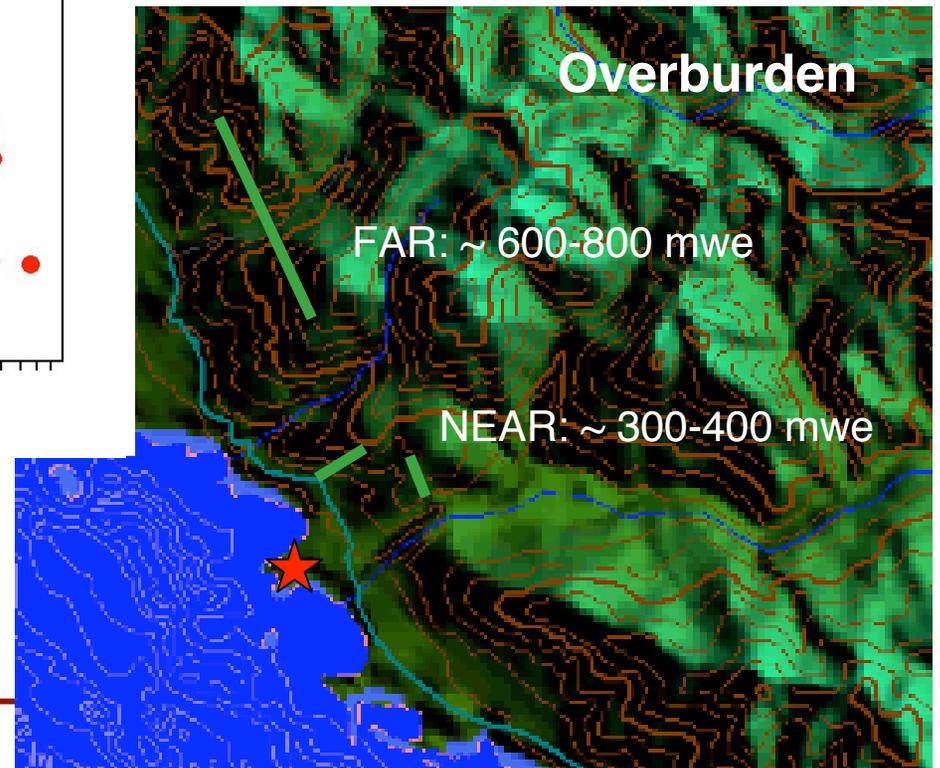


Tunnel excavation required



An Ideal Oscillation Experiment with Variable Baseline?

Possible layout of 2 or 3 detectors at Diablo Canyon



Tunnel excavation required

Neutrino Detectors at Diablo Canyon - NEAR

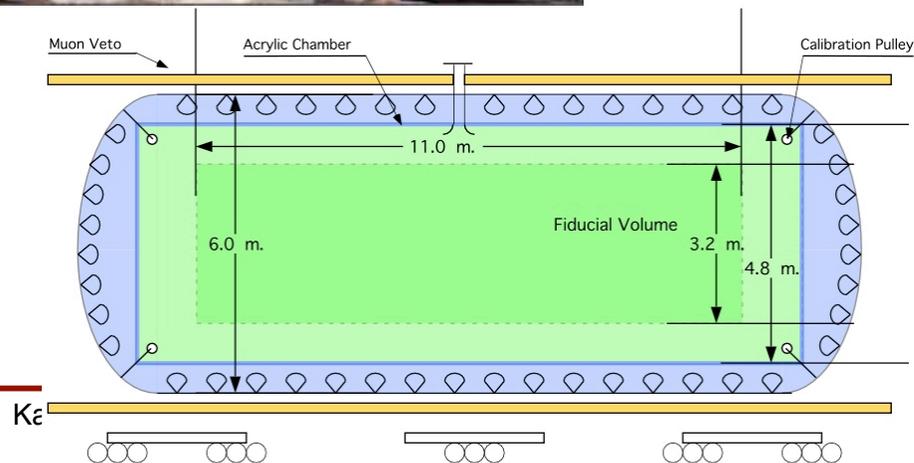
- Space constrained by hills and plant infrastructure
- Best overburden to the North East of power plant



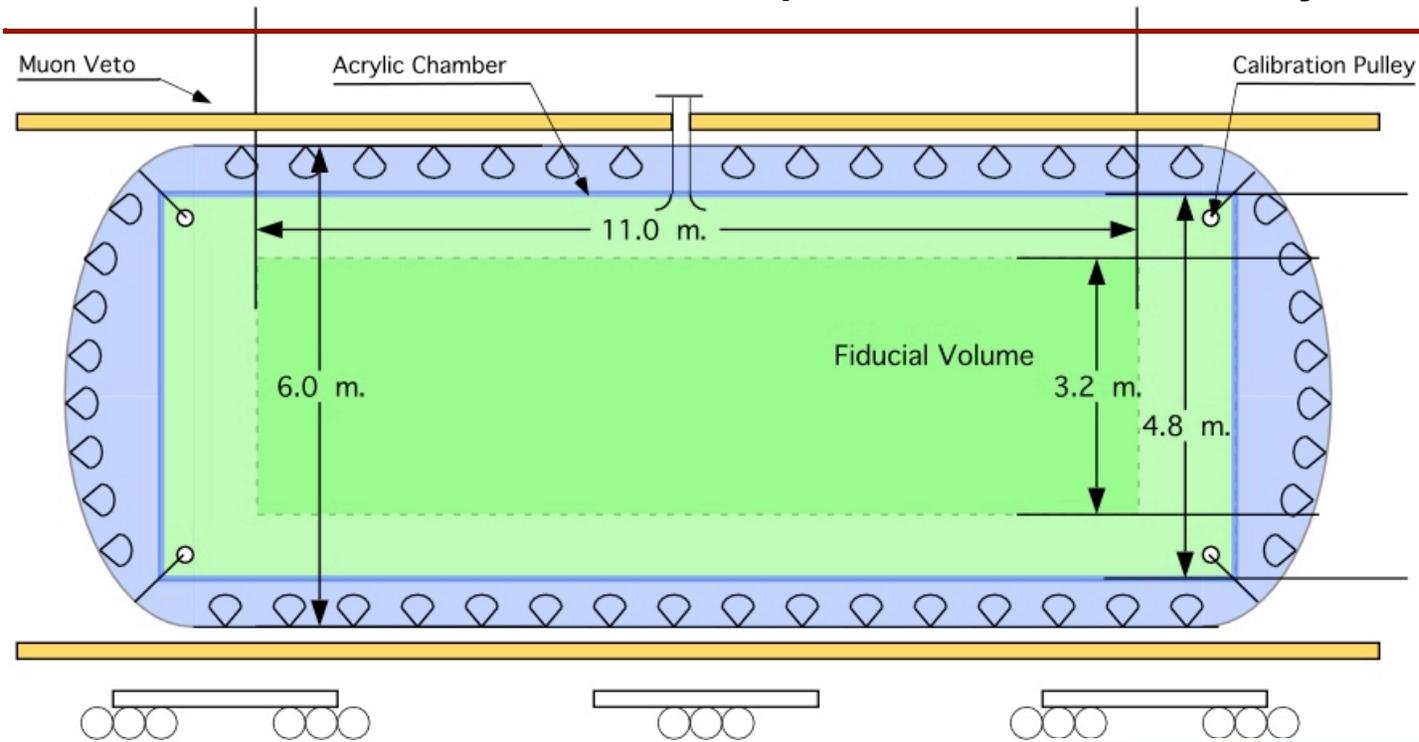
Neutrino Detectors at Diablo Canyon - FAR

- 2 neutrino detectors, railroad-car size
- in tunnels at (variable) distance of

NEAR/FAR I: 0.5-1 km
FAR II: 1.5-3 km



Movable Detector Concept for Diablo Canyon $\bar{\nu}_{13}$ Project



- liquid scintillator detector + active muon veto
- $V_{\text{fiducial}} \sim 80\text{-}100 \text{ t}$
- **Modular, movable detectors**
- **Volume scalable**
 - smaller \square faster*
 - larger \square more sensitive*

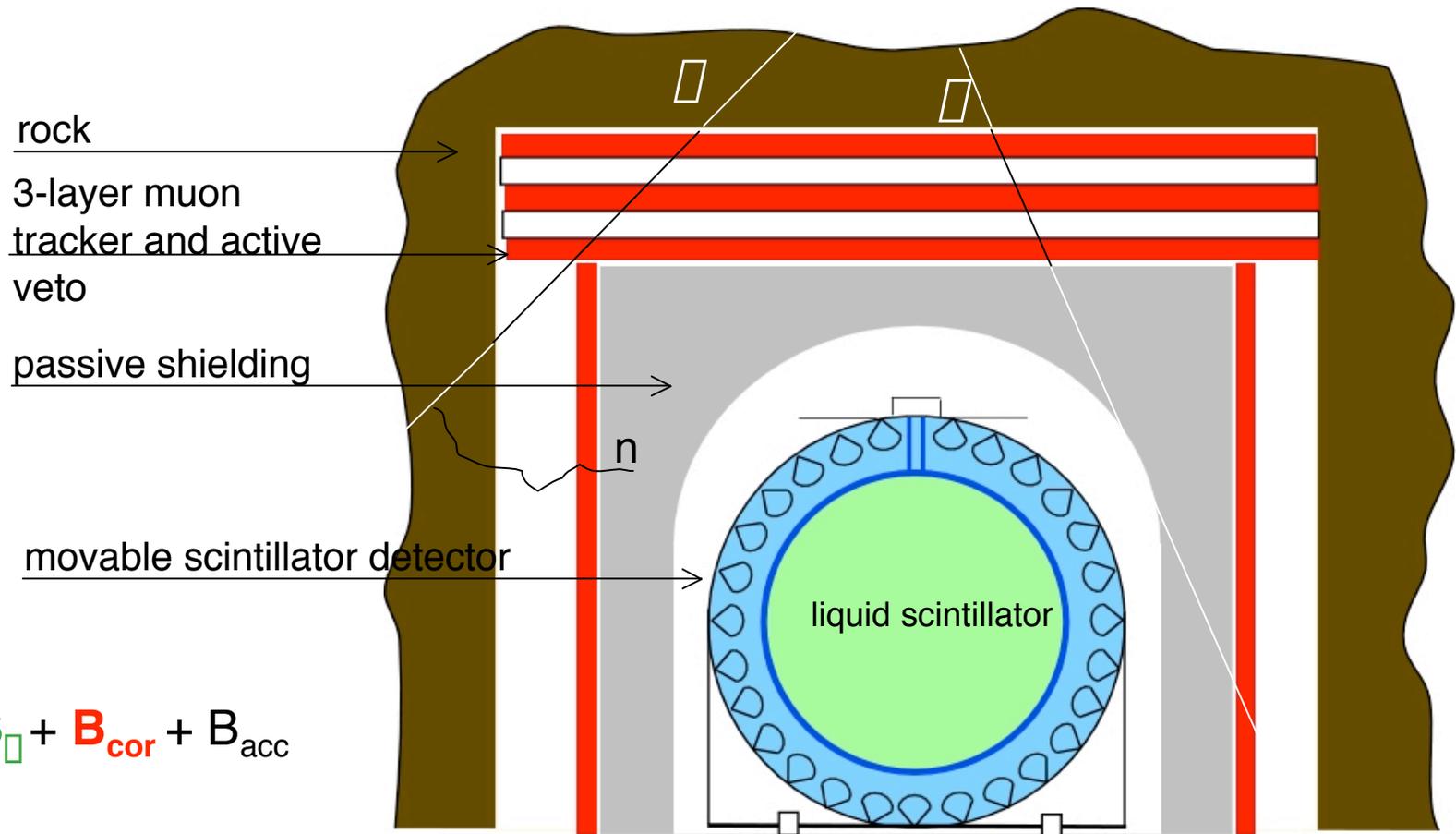


Detector and Shielding Concept

Active muon tracker

+ passive shielding

+ movable, inner liquid scintillator detector



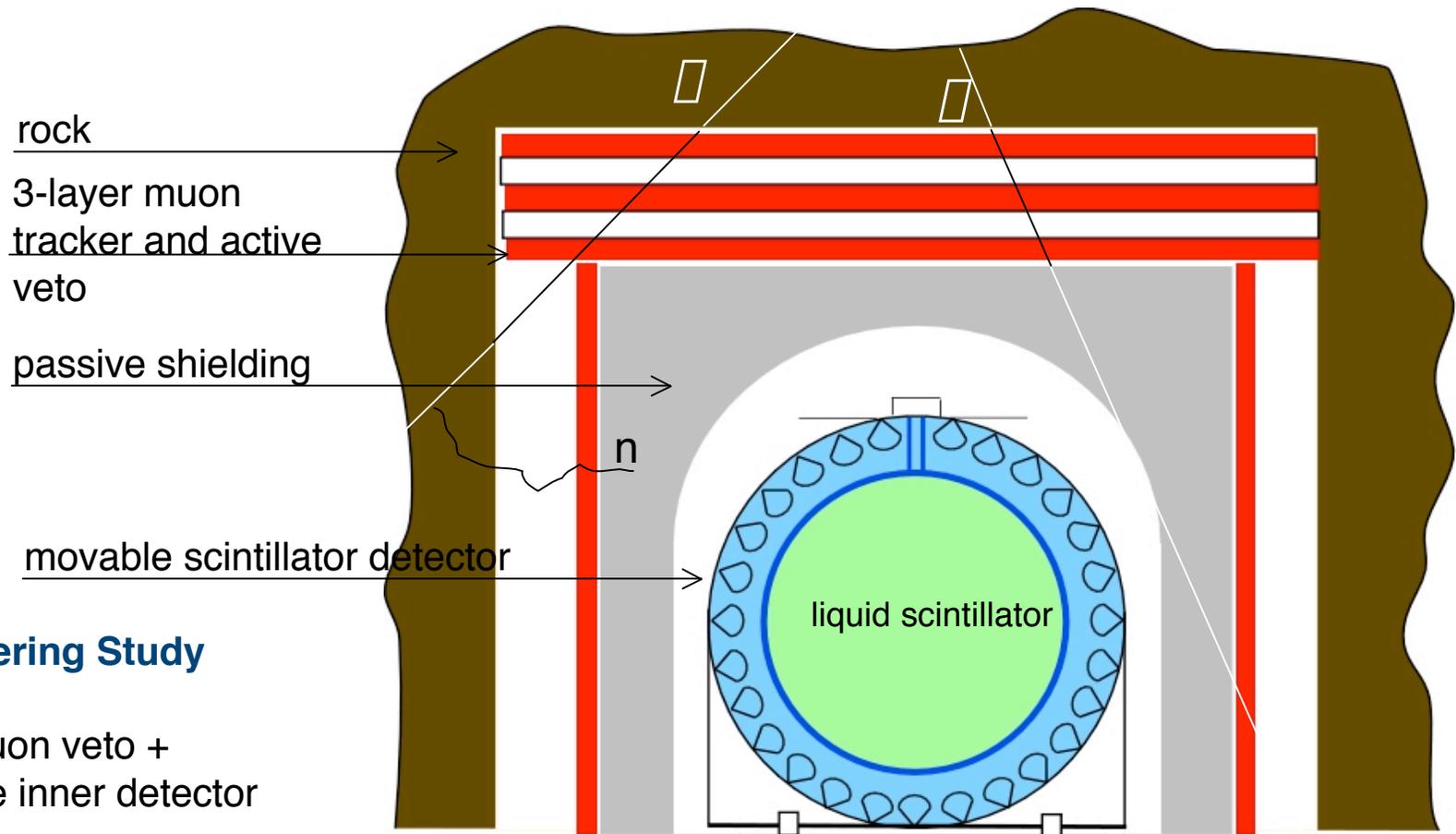
$$N = S_{\square} + B_{cor} + B_{acc}$$

Detector and Shielding Concept

Movable Detector?

Variable baseline to control systematics and demonstrate oscillation effect (if θ_{13} found to be > 0)

Non-trivial for medium-size (~100 t), low-background detector

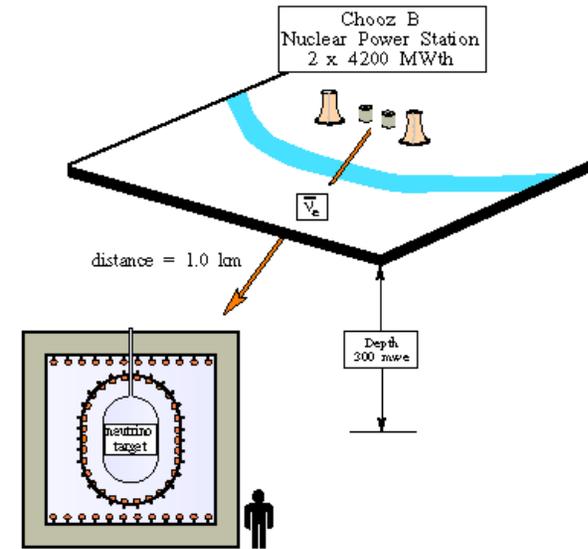


Engineering Study

fixed muon veto +
movable inner detector

Dominant Experimental Systematics

Consider best experiment to date: CHOOZ



Ref: Apollonio et al., hep-ex/0301017

parameter	relative error (%)
reaction cross section	1.9%
number of protons	0.8%
<i>relative</i> detection efficiency	1.5% $\leq 1\%$
reactor power	0.7%
energy released per fission	0.6%
combined	2.7%

relative fiducial vol.

relative

Reactor Flux

- near/far ratio, choice of detector location

$$\sigma_{\text{flux}} < 0.2\%$$

Detector Efficiency

- built near and far detector of same design
- calibrate *relative* detector efficiency
- *variable* baseline may be necessary

$$\sigma_{\text{rel eff}} \leq 1\%$$

Target Volume &

- no fiducial volume cut

$$\sigma_{\text{target}} \sim 0.3\%$$

Backgrounds

- external active and passive shielding for correlated backgrounds

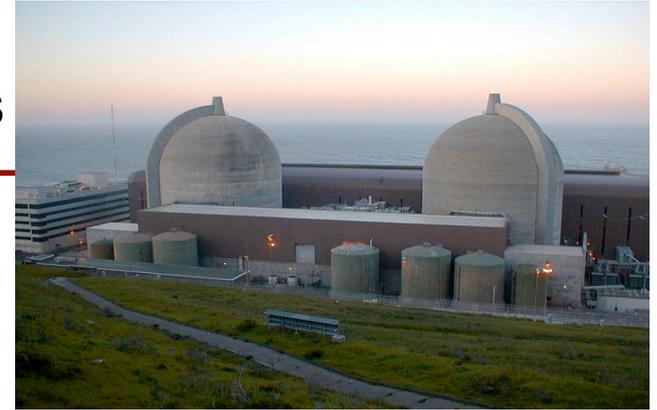
$$\sigma_{\text{acc}} < 0.5\%$$

$$\sigma_{\text{n bkgd}} < 1\%$$

Note: list not comprehensive

$$\text{Total } \sigma_{\text{syst}} \sim 1-1.5\%$$

Flux Systematics with Multiple Reactor Cores



$$\phi_i = \phi_A^0 \frac{1}{R_A^2} P_A + \phi_B^0 \frac{1}{R_B^2} P_B$$

Individual reactor flux contributions and systematics cancel *exactly* if

Condition 1: $\frac{R_A^2}{R_B^2} = \text{const.}$ $1/r^2$ fall-off of reactor flux the same for all detectors.

Condition 2: $P_A \approx P_B \approx P$ Survival probabilities are approximately the same

□ Approximate flux cancellation possible at other locations

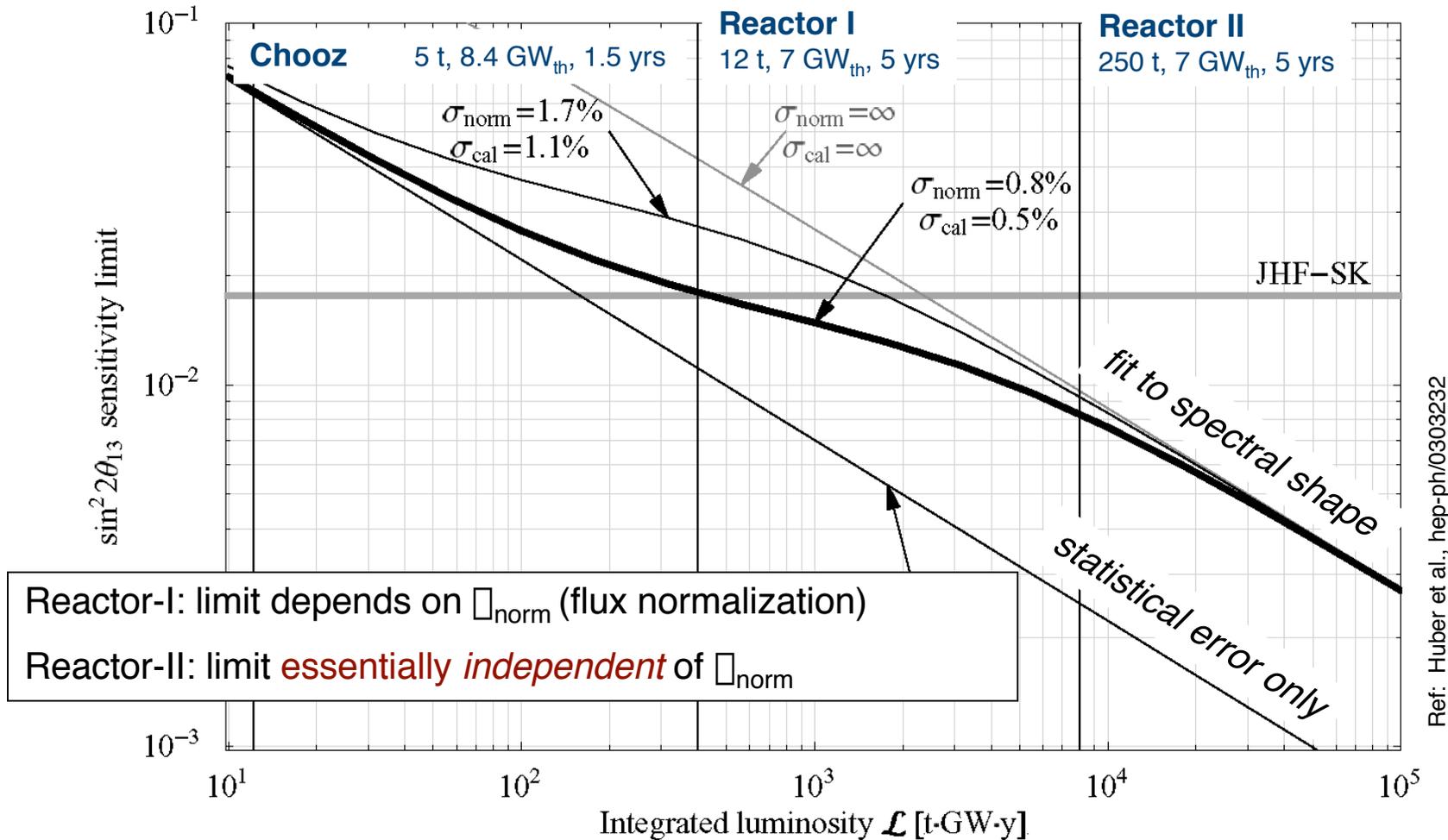
	Relative Error Between Detector 1 and 2	
	rate	shape
Relative flux error (1%)	< 0.6%	< 0.01%
Reactor core separation (100 m)	< 0.14%	< 0.1%
Finite detector length (10 m)	< 0.2%	< 0.1%

- Shape analysis largely insensitive to flux systematics.
- Distortions are robust signature of oscillations.

Sensitivity to $\sin^2 2\theta_{13}$ at 90% CL

ϵ_{cal} relative near/far energy calibration

ϵ_{norm} relative near/far flux normalization



Sensitivity and Complementarity of θ_{13} Experiments

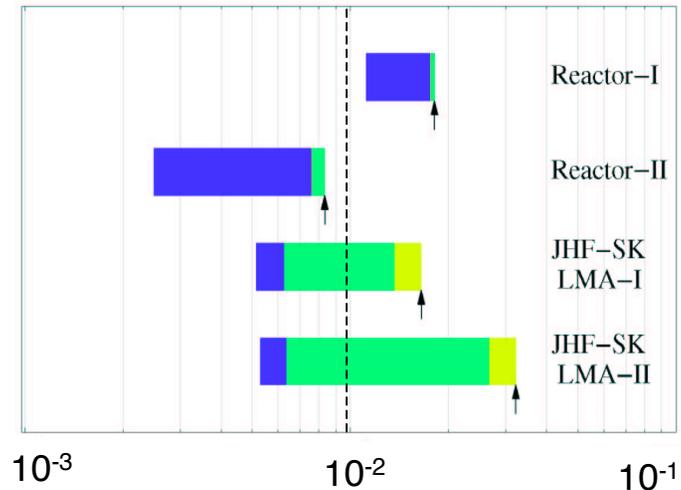
Reactor Neutrino Measurement of θ_{13}

- No matter effect
- Correlations are small, no degeneracies
- Insensitive to solar parameters $\theta_{12}, \Delta m_{21}^2$

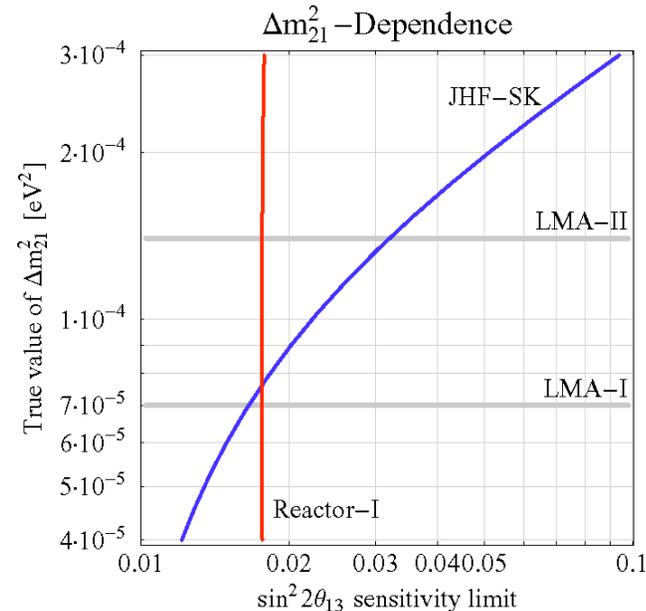
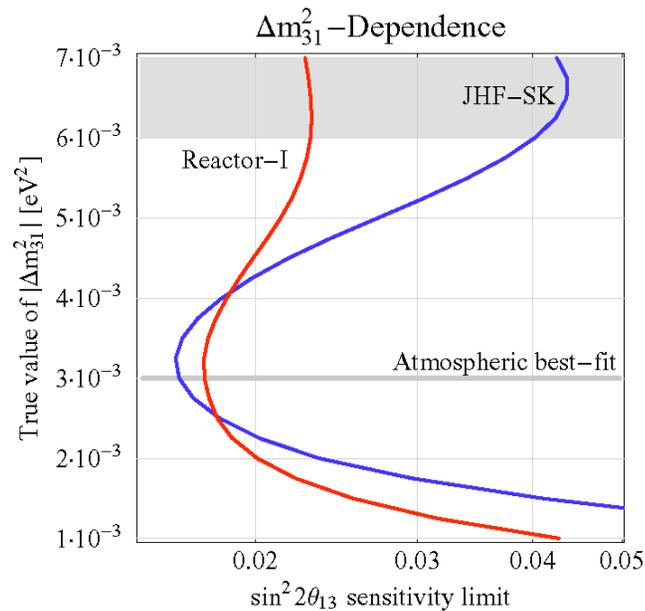
$$\sin^2 2\theta_{13} < 0.01-0.02 \text{ @ } 90 \text{ C.L.}$$

within reach of reactor θ_{13} experiments

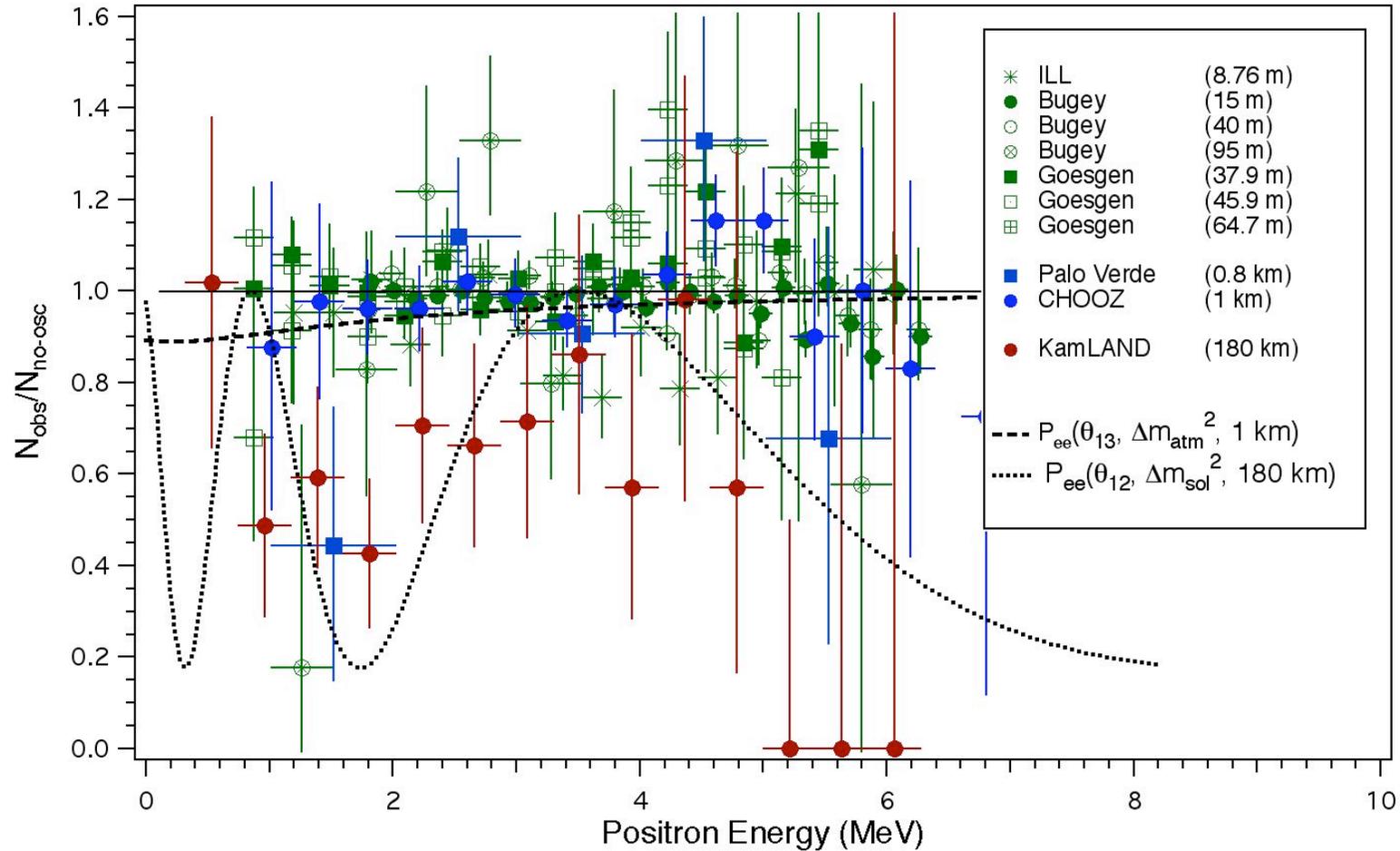
Sensitivity to $\sin^2 2\theta_{13}$



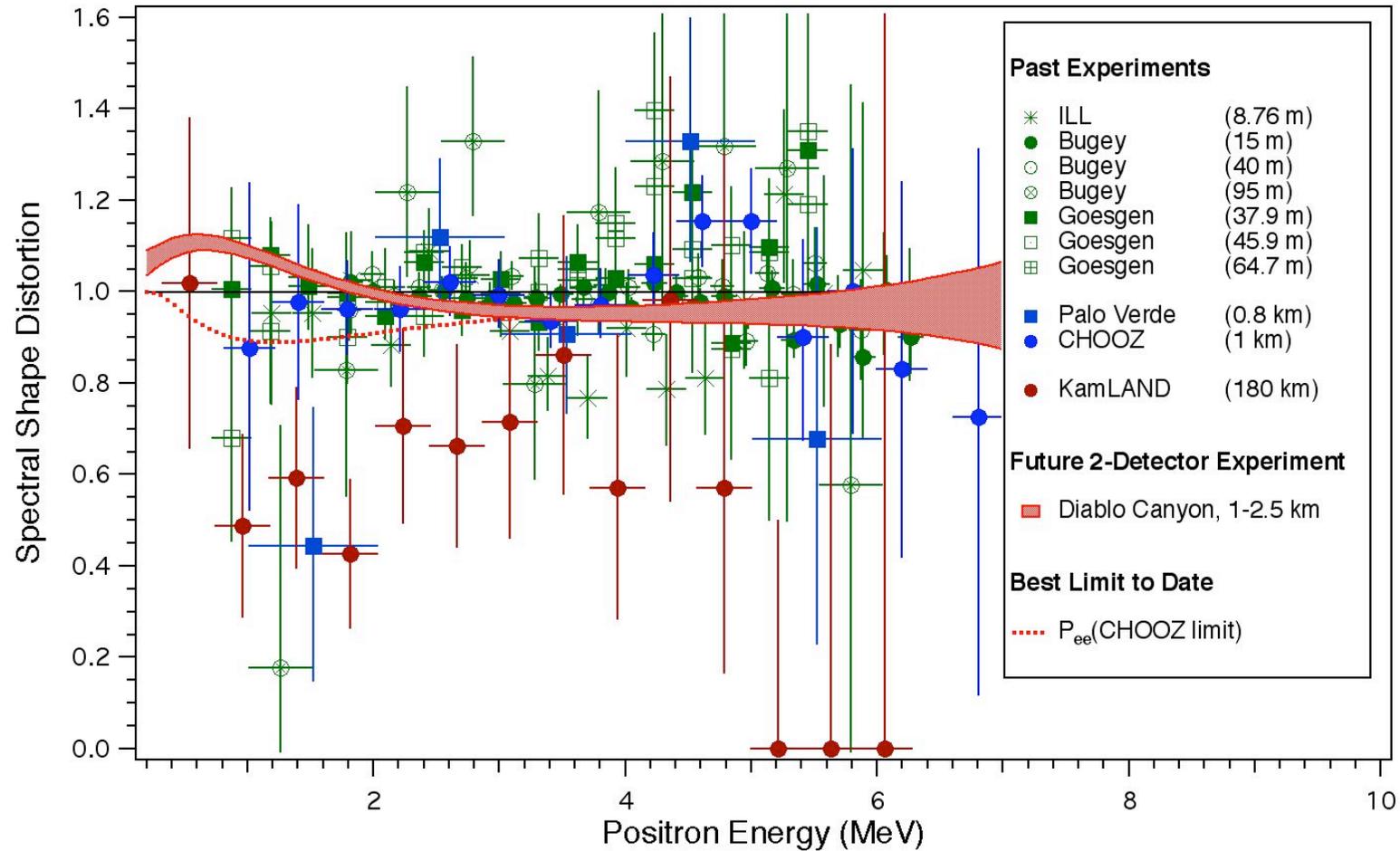
Ref: Huber et al., hep-ph/0303232



Past and Present Reactor Neutrino Experiments



Future Diablo Canyon Experiment



50 Years of Scientific Discoveries at Reactors

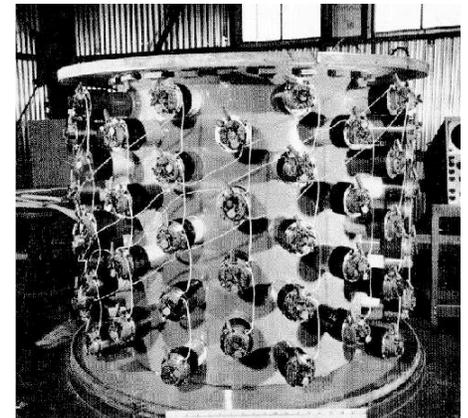


1956

Discovery of neutrinos in the US:
First detection of reactor neutrinos

1990's

Reactor neutrino flux measurements in US and Europe



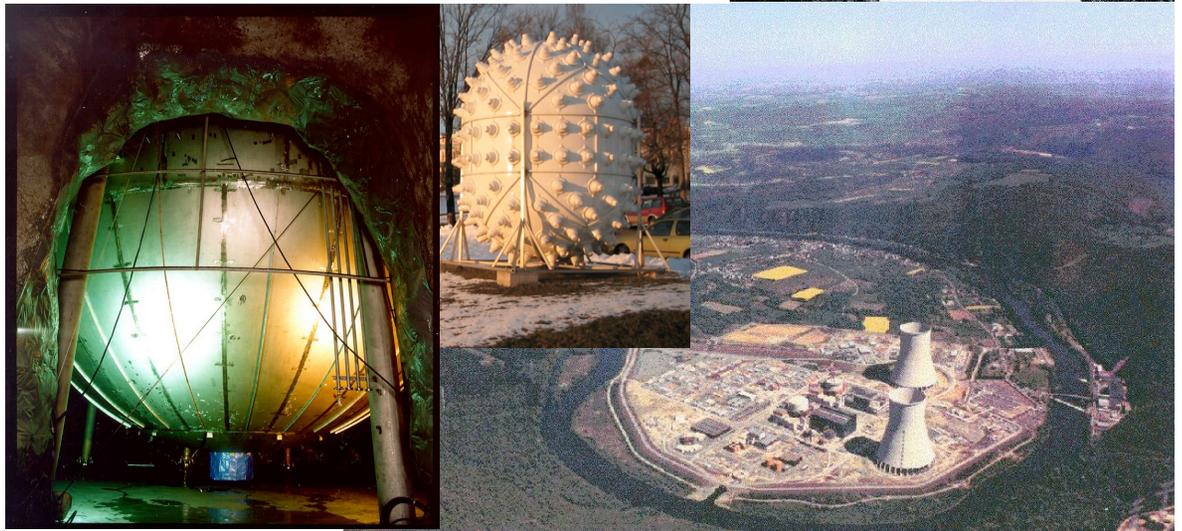
1995

Nobel Prize to Fred Reines
at UC Irvine

2002

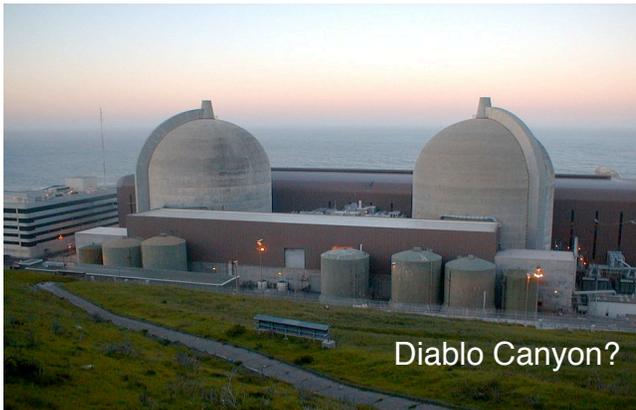
Discovery of massive
neutrinos and oscillations

50 years of discoveries



Next Step

Understanding the role of neutrinos in the early Universe.
Why is there matter and not antimatter?



Diablo Canyon?

.03, June 11, 2003

Summary: Reactor Measurement of θ_{13}

- Reactor neutrino oscillation experiment is **promising option** to measure θ_{13} .
- Novel reactor oscillation experiment gives **clean measurement of $\sin^2 2\theta_{13}$** , no degeneracies, no matter effects.

2 or 3 detectors

variable baseline

largely independent of absolute reactor flux and systematics

- Sensitivity of **$\sin^2 2\theta_{13} \sim 0.01$** comparable to next-generation accelerator experiments. Complementary to long-baseline program. Allows combined analysis of reactor and superbeam experiments.
- Negotiations with US power plants underway. Diablo Canyon is an attractive possibility.

<http://theta13.lbl.gov/>